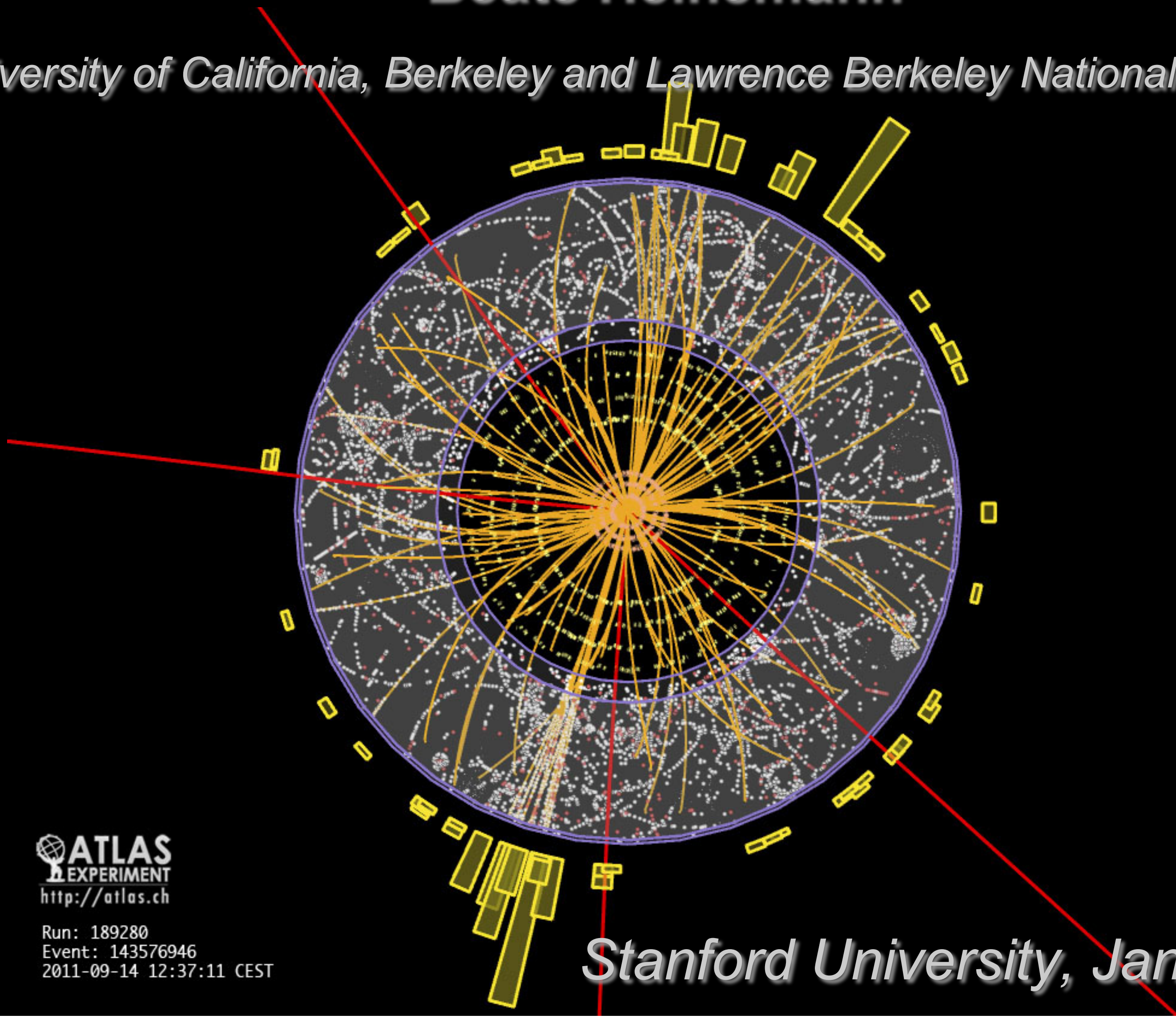
The First Three Years at the LHC

Beate Heinemann

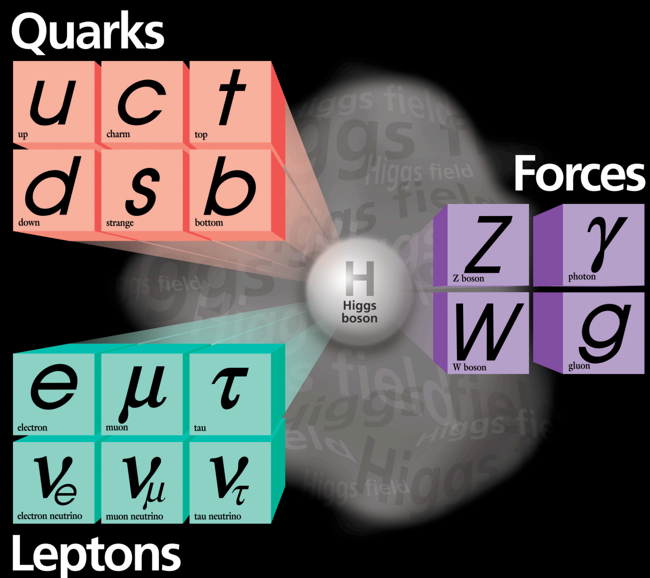
University of California, Berkeley and Lawrence Berkeley National Laboratory

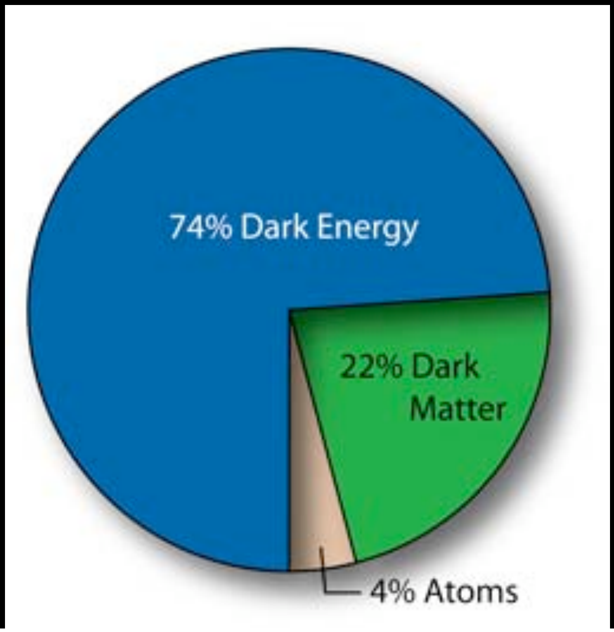


Stanford University, January 2013

What Do We Hope to find at LHC?

- Answers to very fundamental and simple questions:
  - **Why do particles have mass?**
    - Possible answer: The Higgs boson
  - **Why is gravity so weak?**
    - Possible answers: supersymmetric particles, extra spatial dimensions
  - **What is the Dark Matter?**
    - Possible answer: the lightest supersymmetric particle
  - **The unexpected …**



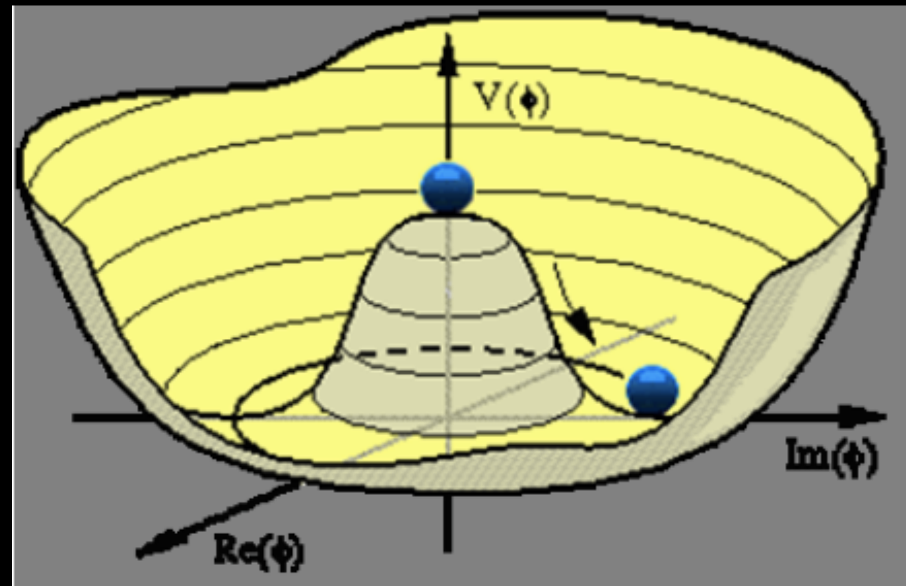


The Higgs Mechanism

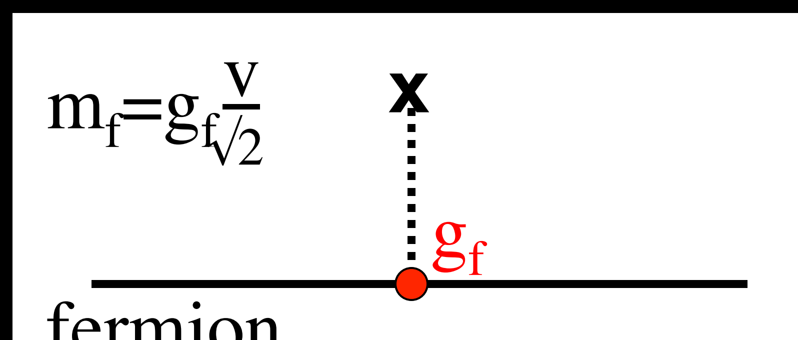
- 1964
  - P. Higgs
  - R. Brout, F. Englert
- New scalar self-interacting field with 4 d.o.f.:

$$V(\Phi) = \frac{\lambda}{4}(\Phi^\dagger\Phi - \frac{1}{2}v^2)^2$$

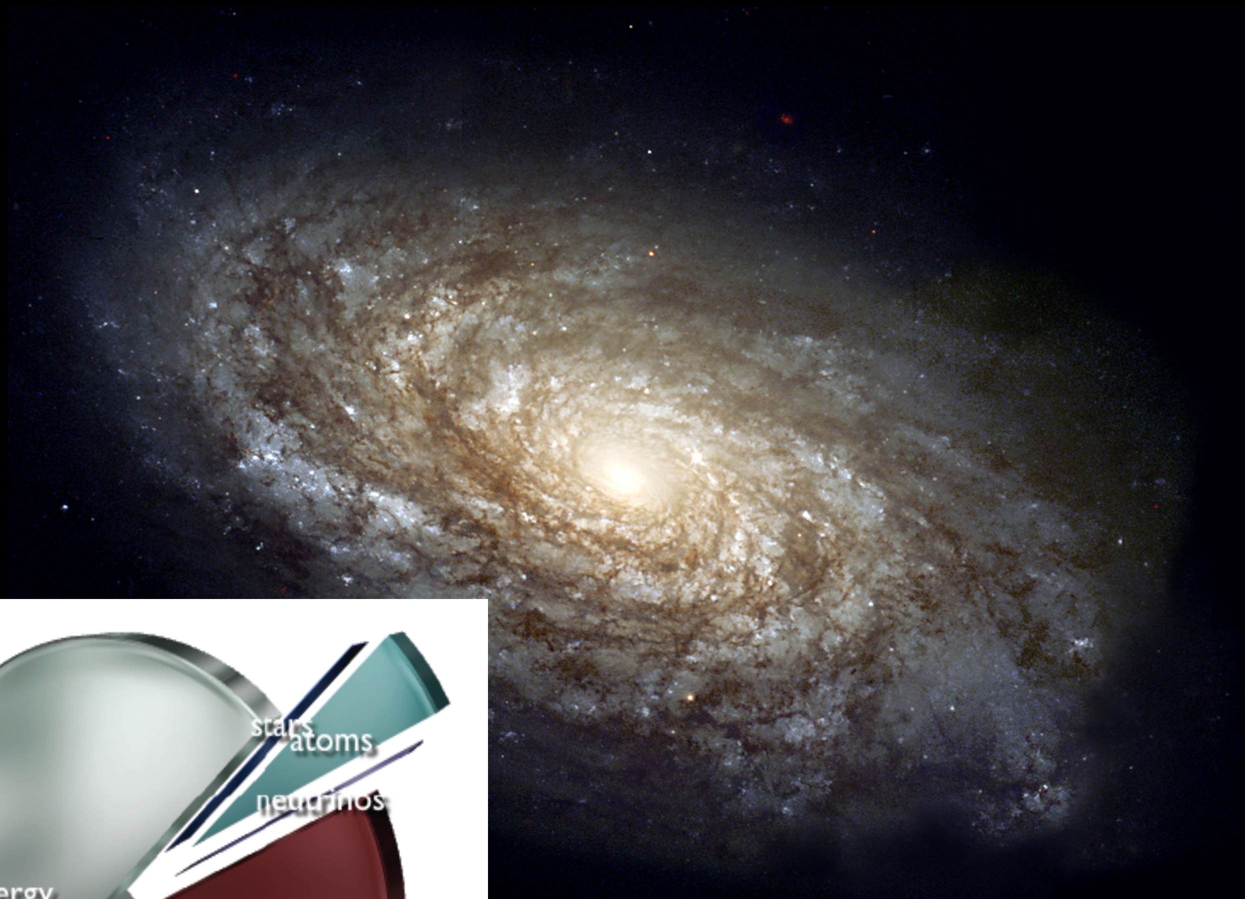
- Ground state: non-zero-value breaks electroweak symmetry generating
  - 3 Goldstone bosons: $W^\pm_L, Z_L$
  - 1 neutral Higgs boson
- Masses of fermions m_f proportional to unknown Yukawa couplings g_f

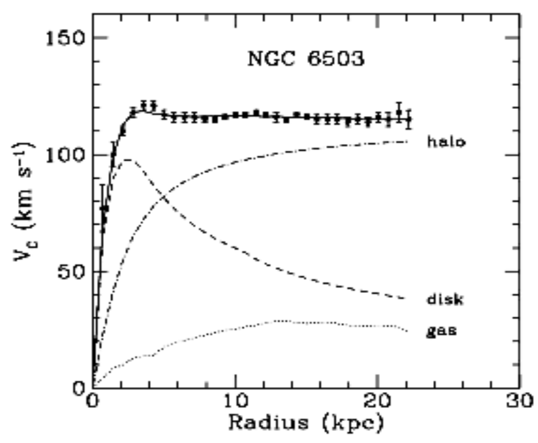


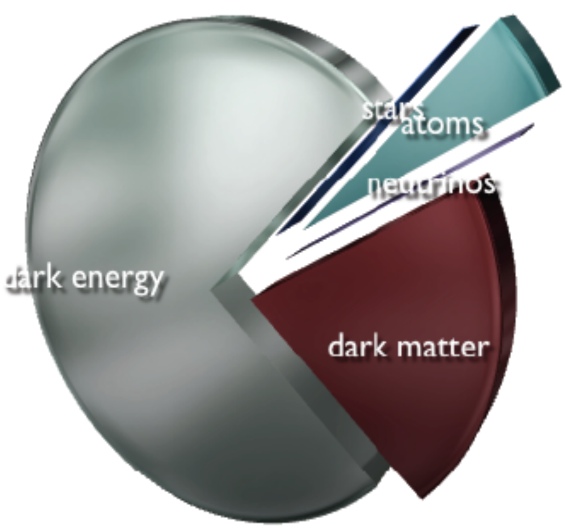
$$\langle\Phi^0\rangle = v/\sqrt{2}, \text{ where } v = 246 \text{ GeV}.$$



What is the Dark Matter?





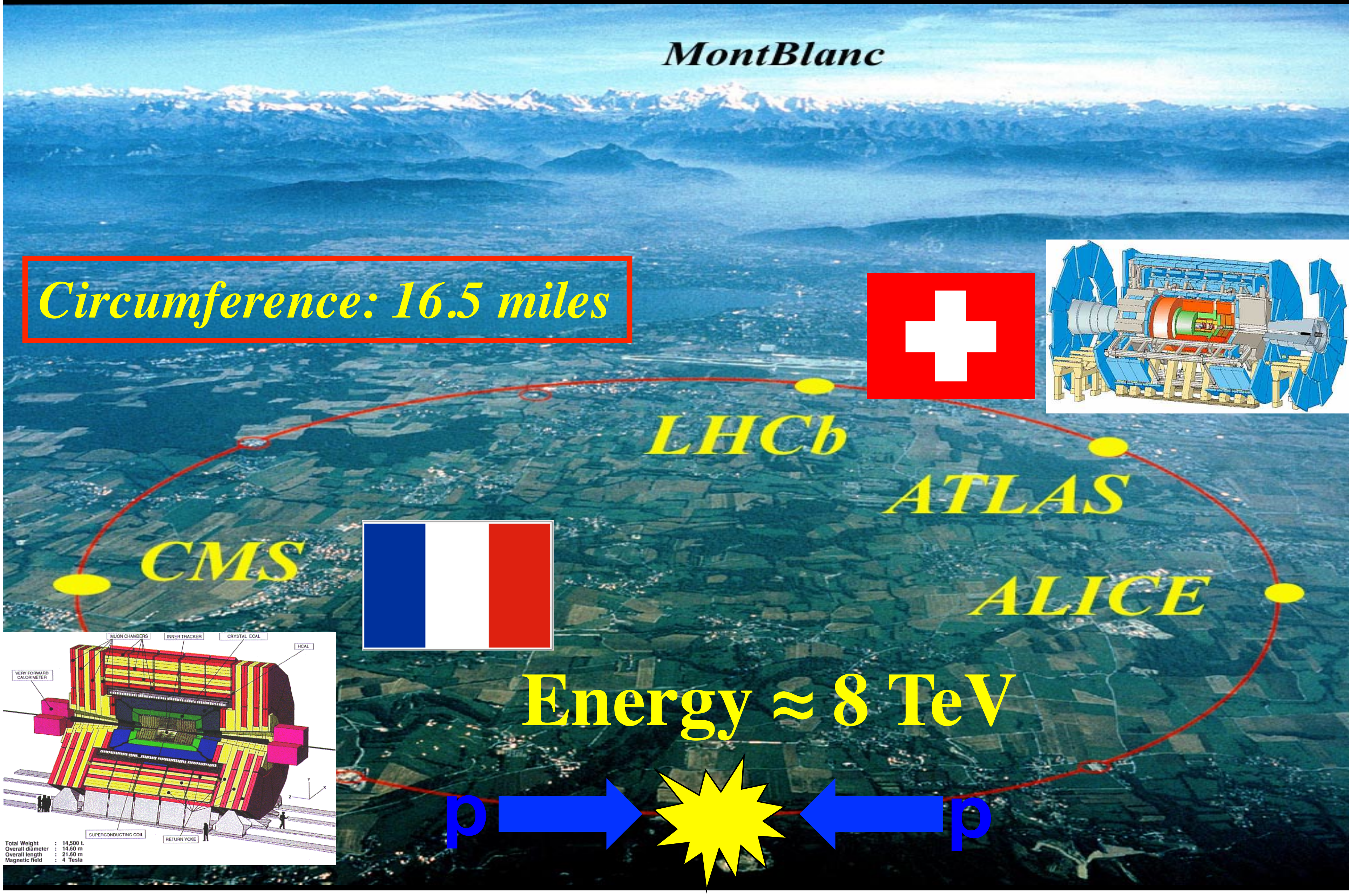


$$\frac{\text{matter}}{\text{all atoms}} = 5.70^{+0.39}_{-0.61}$$

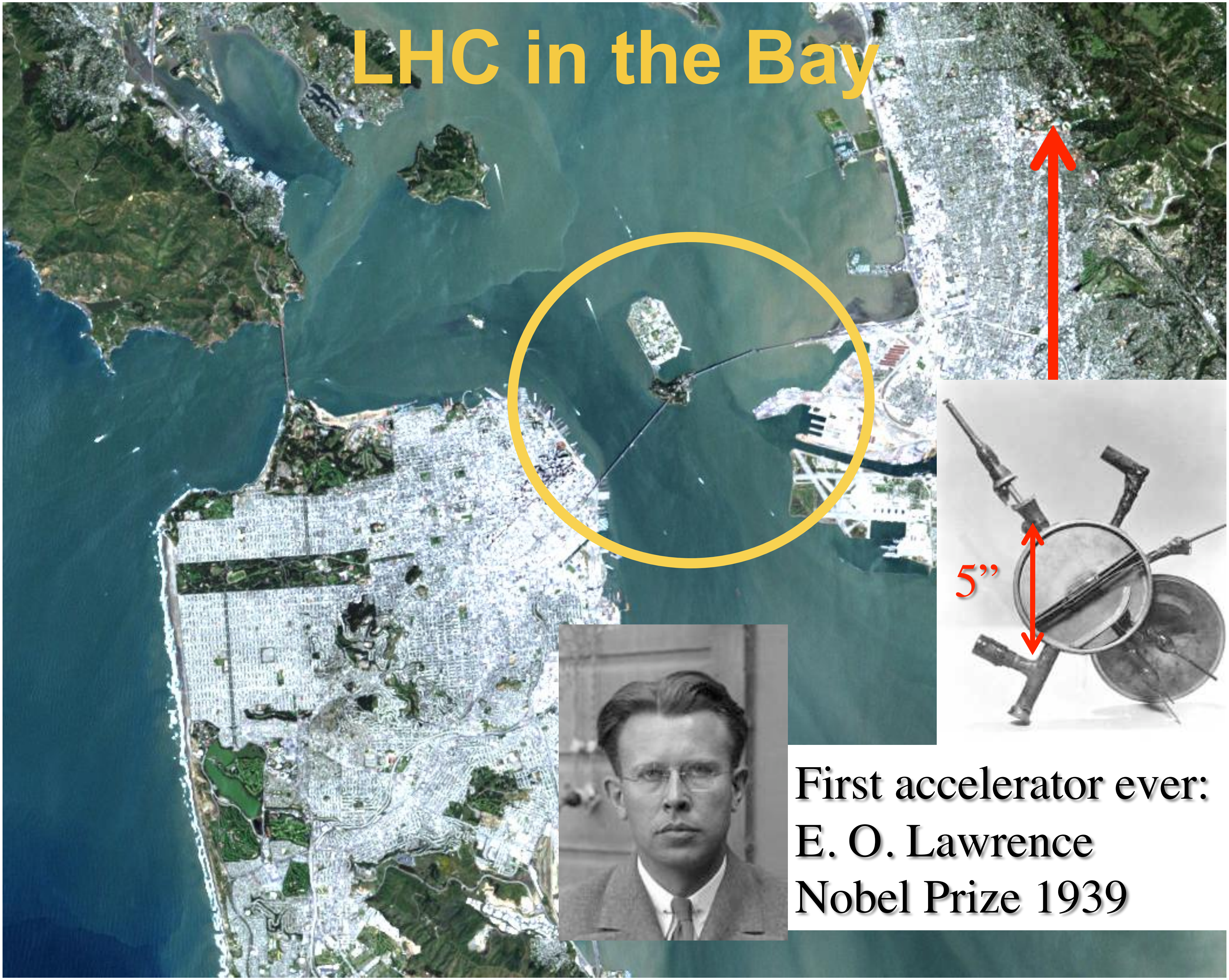
Standard Model only accounts for 20% of the matter of the Universe:

Many theories predict production of dark matter particles at the LHC

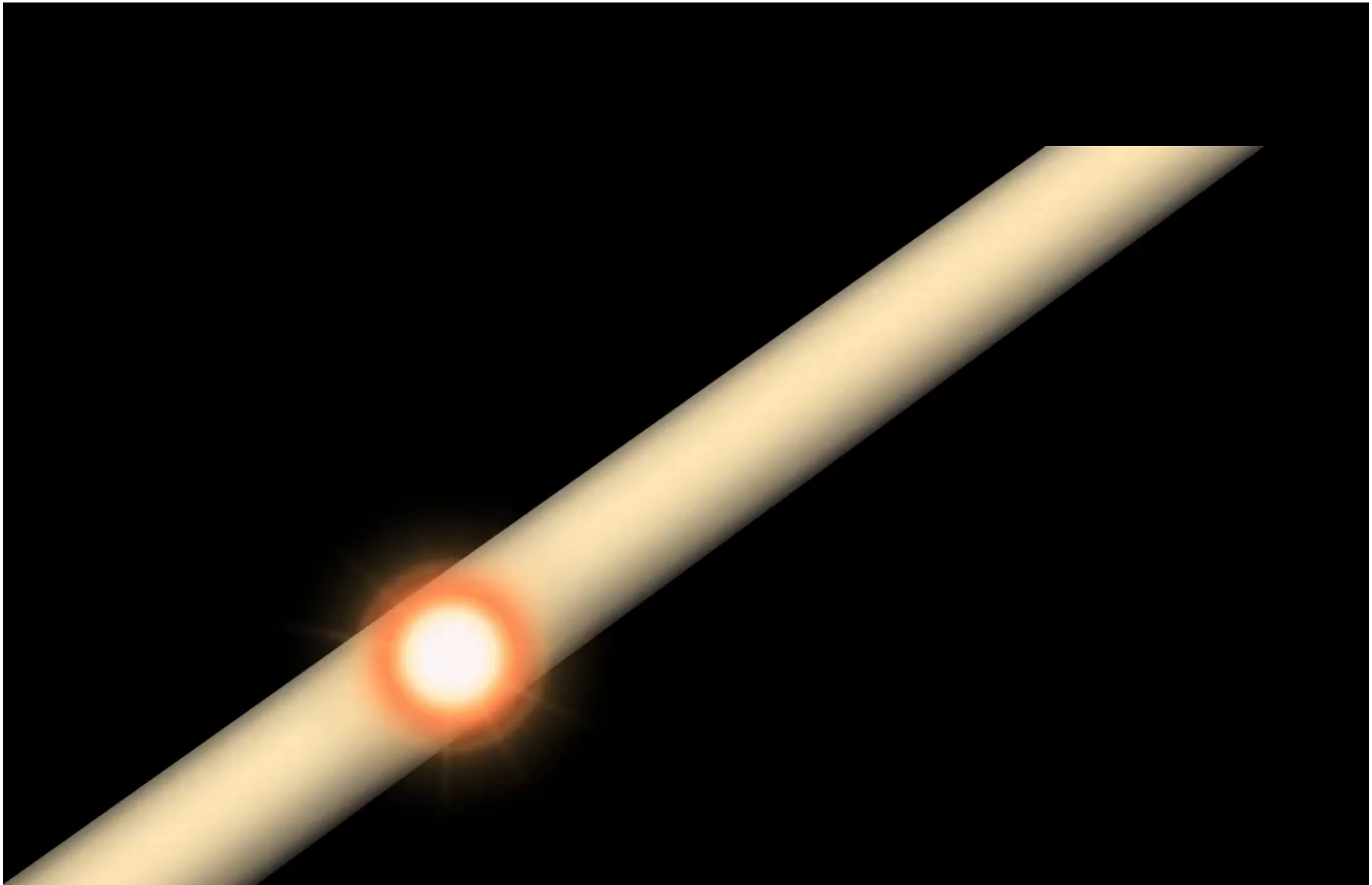
The Large Hadron Collider (LHC)



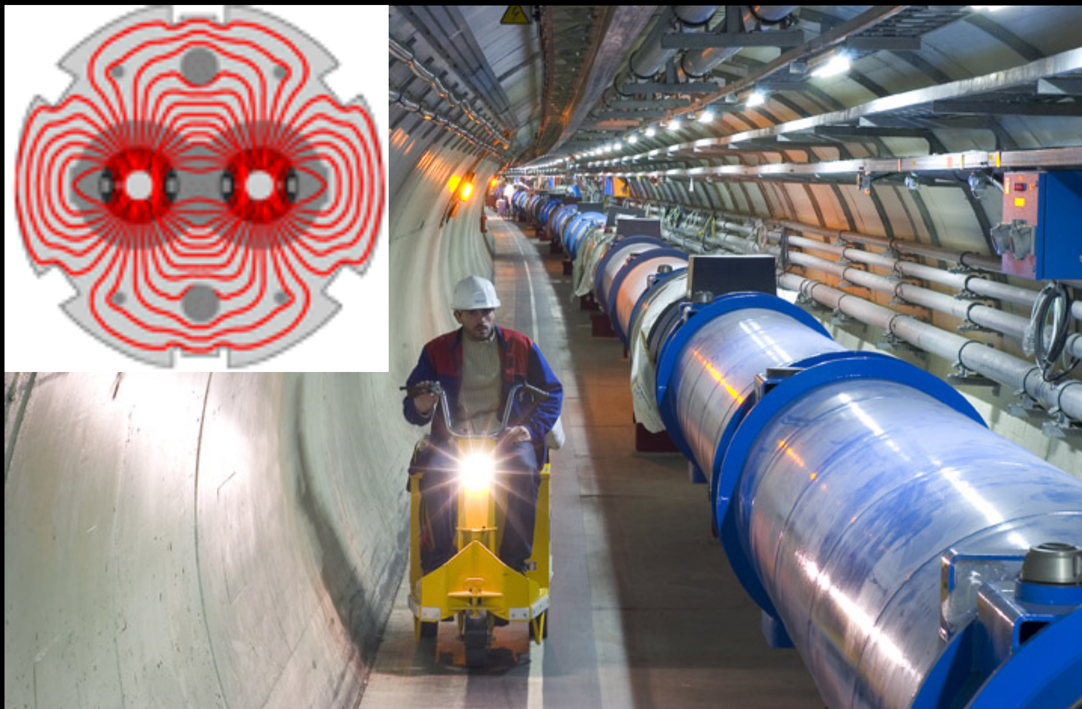
LHC in the Bay



First accelerator ever:
E. O. Lawrence
Nobel Prize 1939



LHC Accelerator

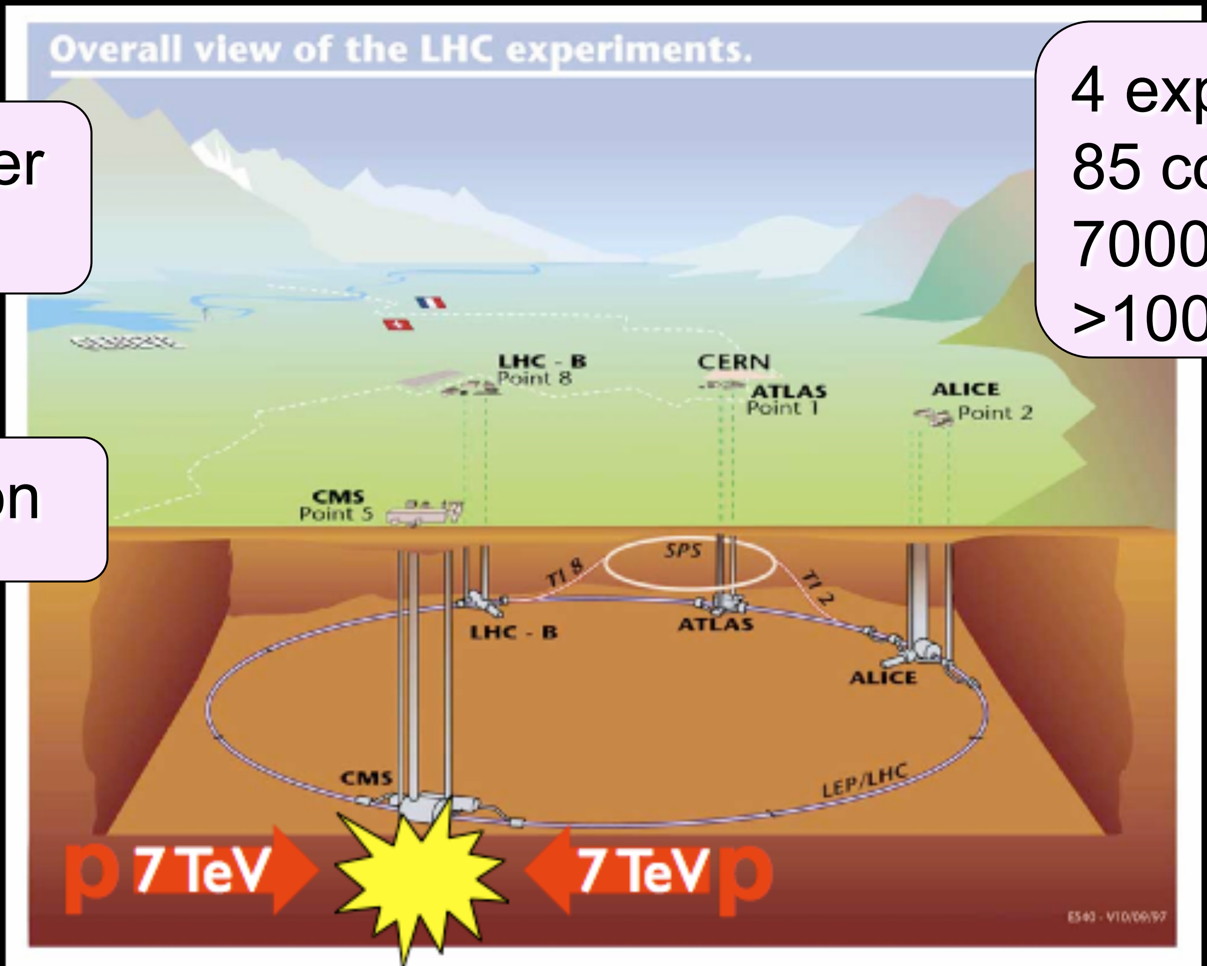


- 30,000 tons of 8.4T dipole magnets
- Cooled to 1.9K with 90 tons of liquid helium
- Energy of beam = 362 MJ
  - Kinetic energy of 15 ton truck at 500 mph

The Large Hadron Collider

300ft under ground

~$8 billion

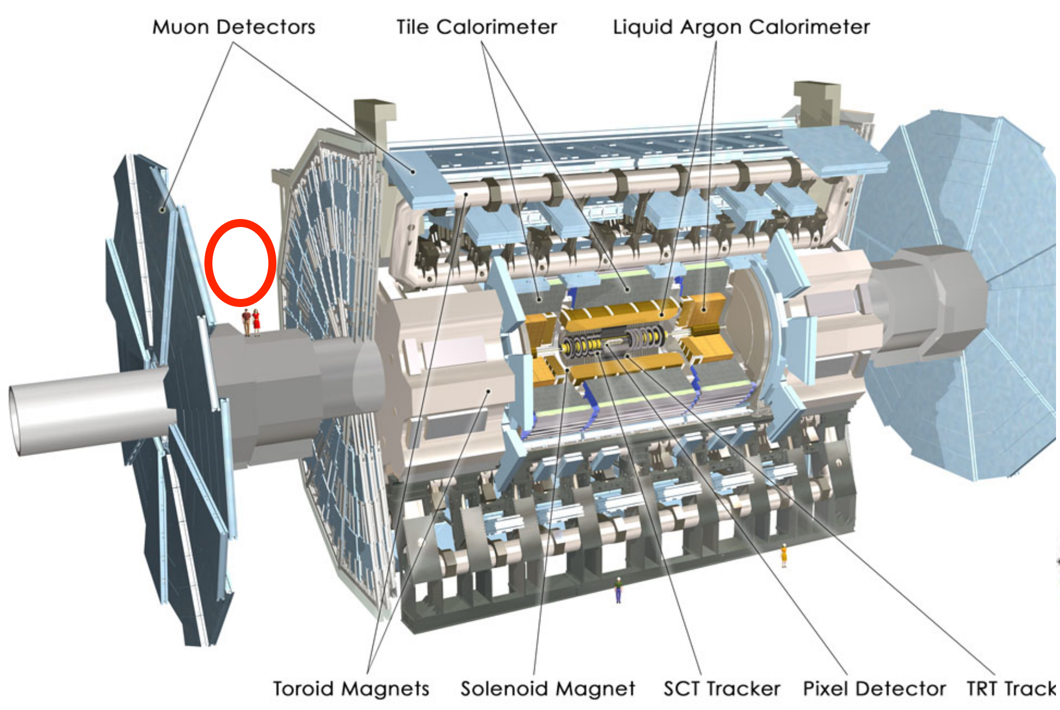


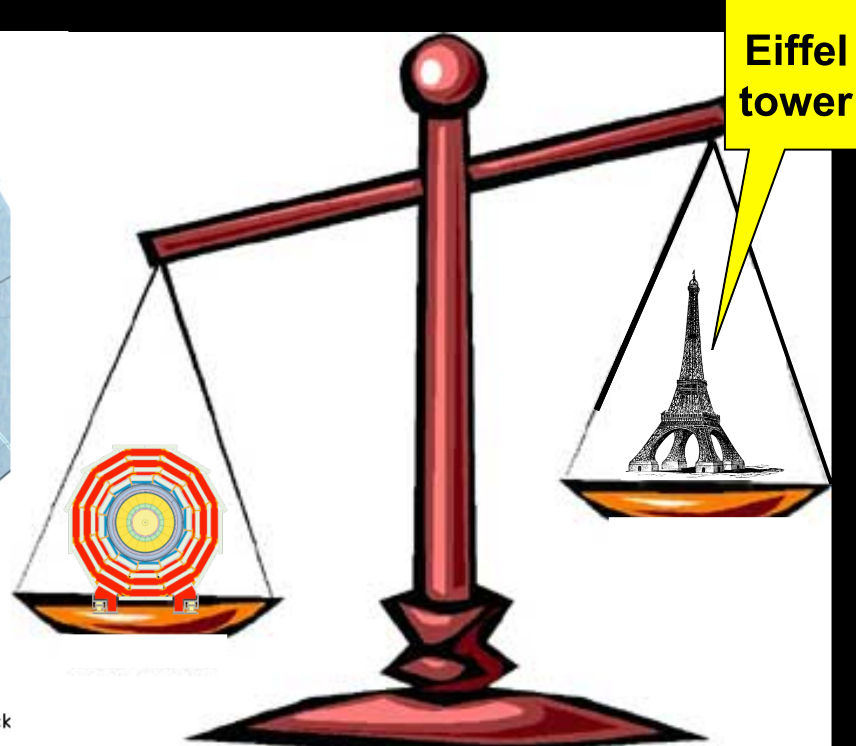
4 experiments
85 countries
7000 scientists
>1000 students

- At border of Switzerland and France

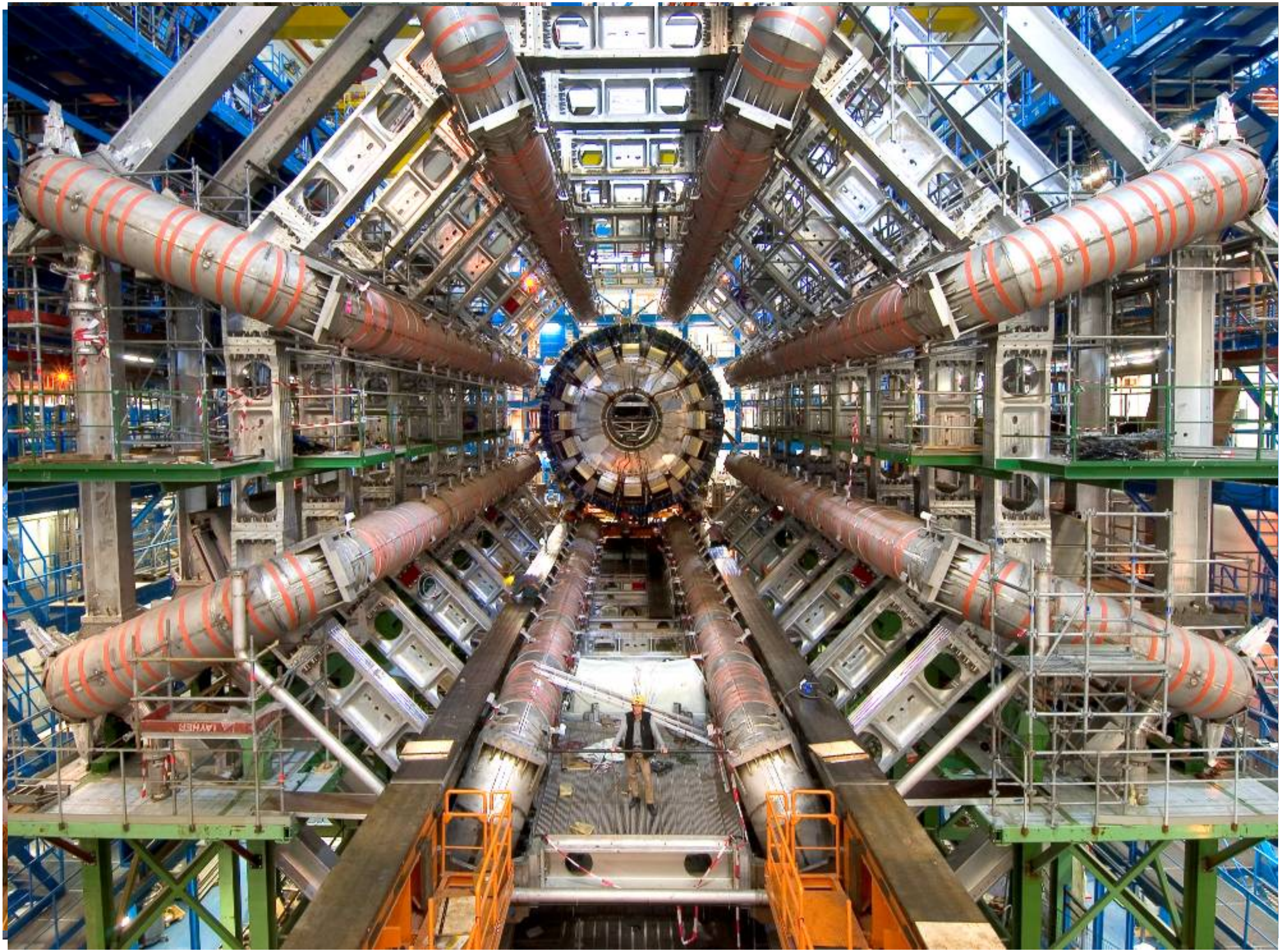
Stanford Students at CERN

ATLAS and CMS Detectors

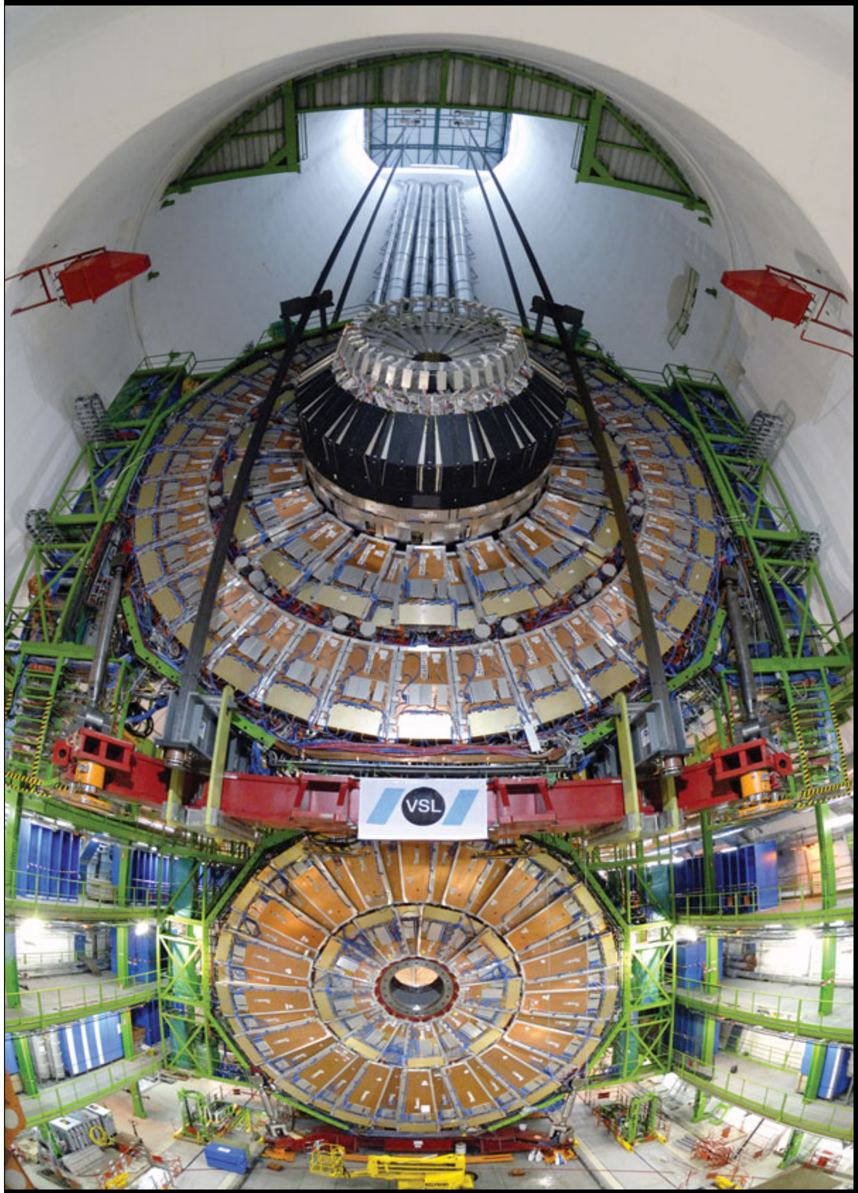


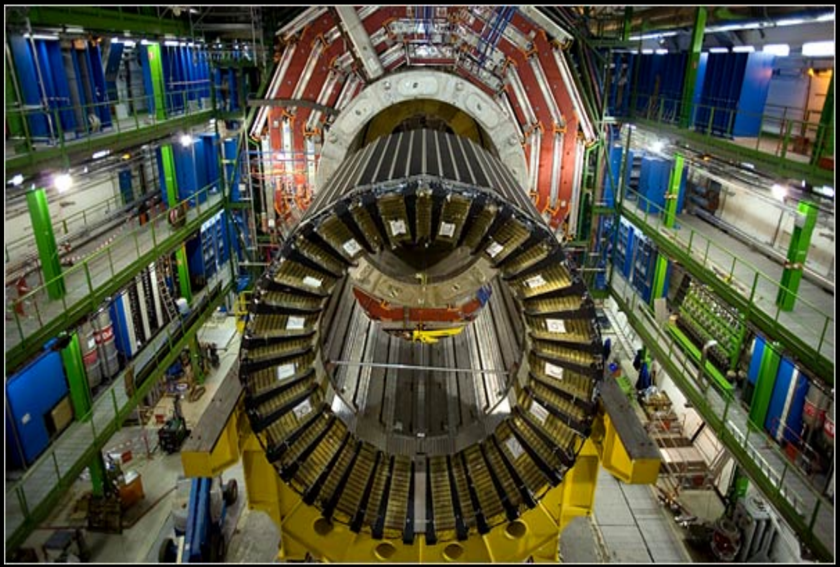


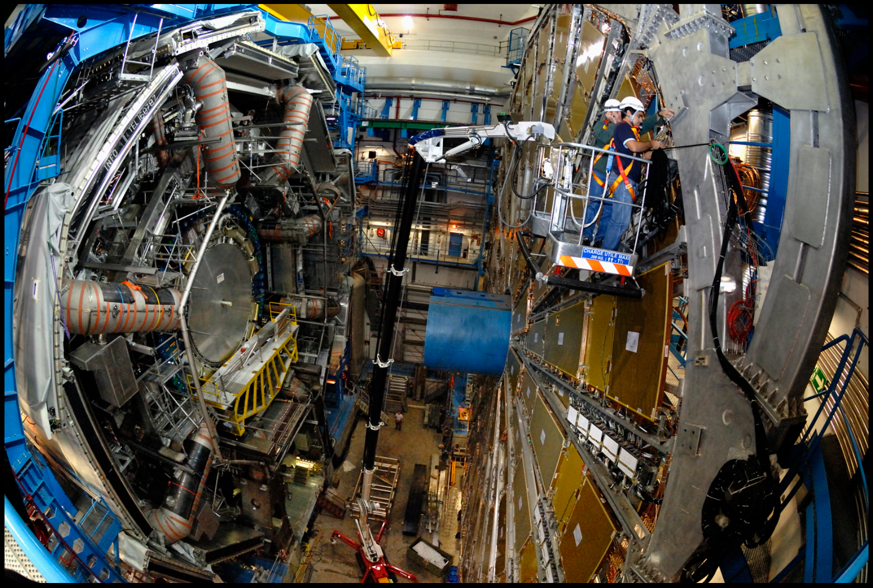
	Weight (tons)	Length (m)	Height (m)
ATLAS	7,000	42	22
CMS	12,500	21	15



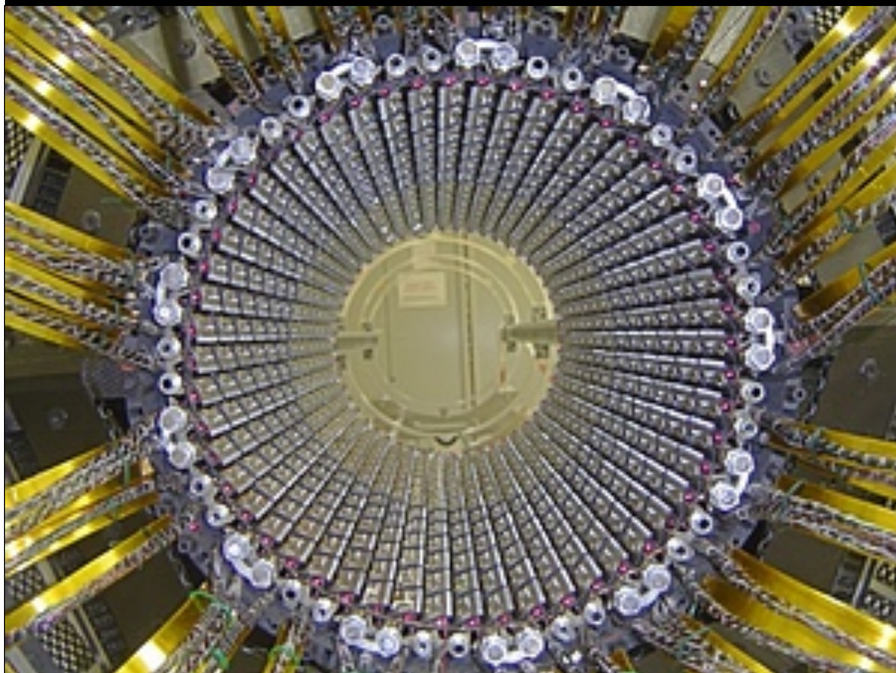
ATLAS and CMS Detectors

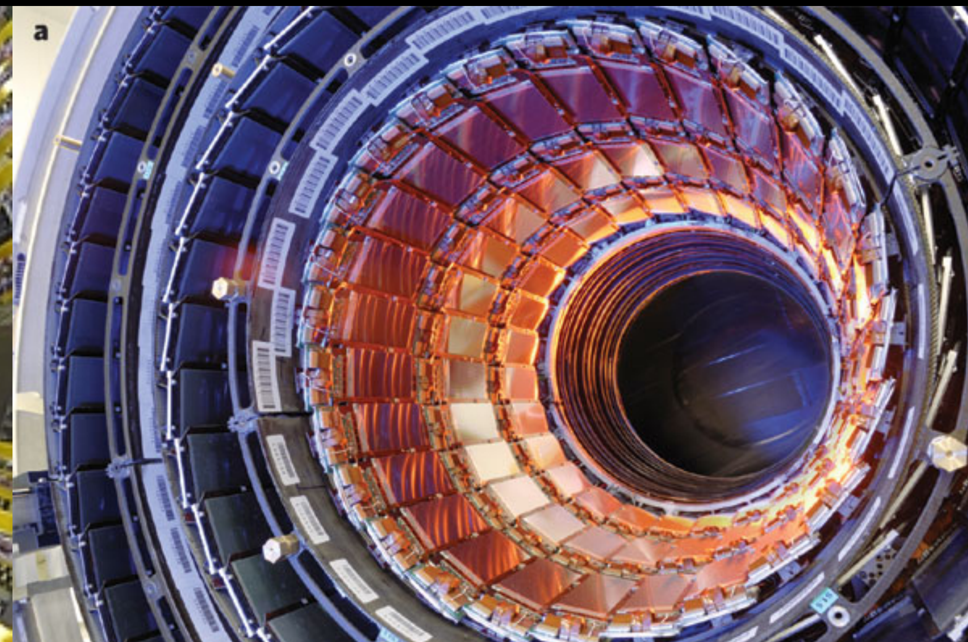


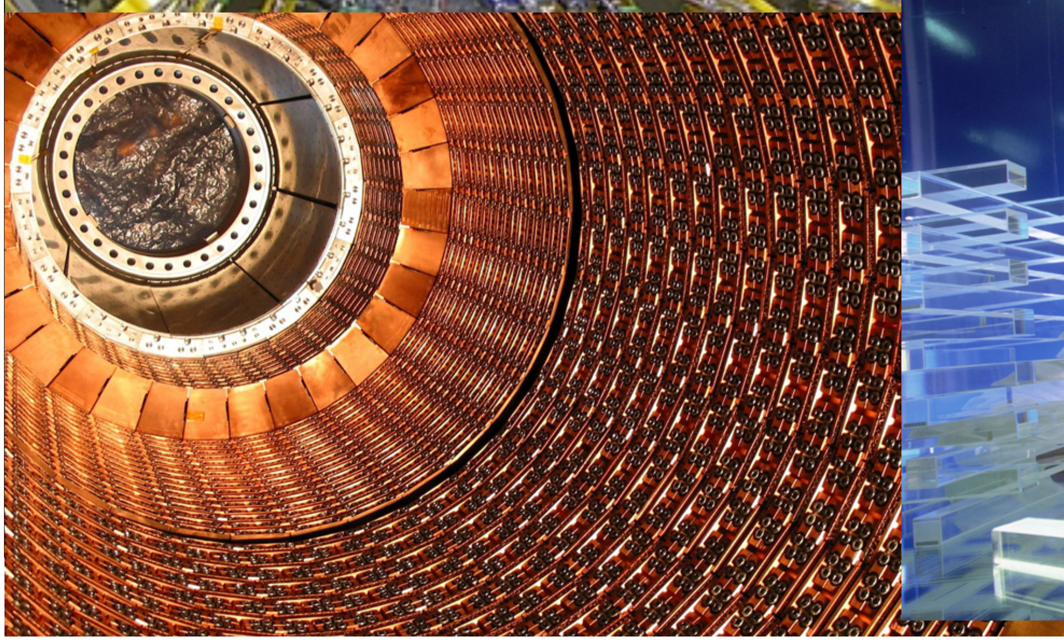




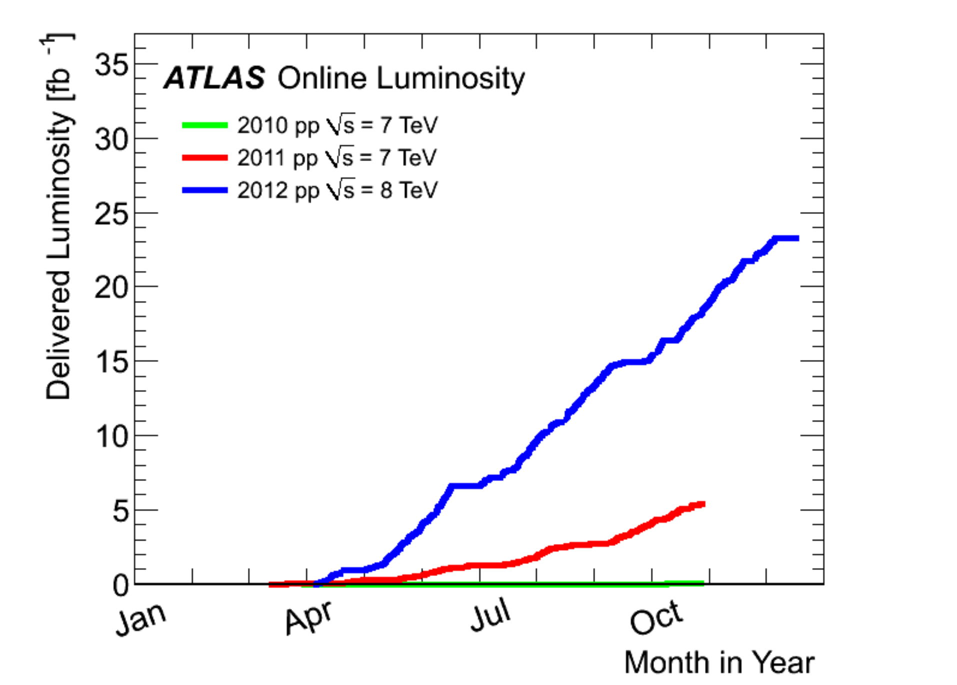
ATLAS and CMS Detectors



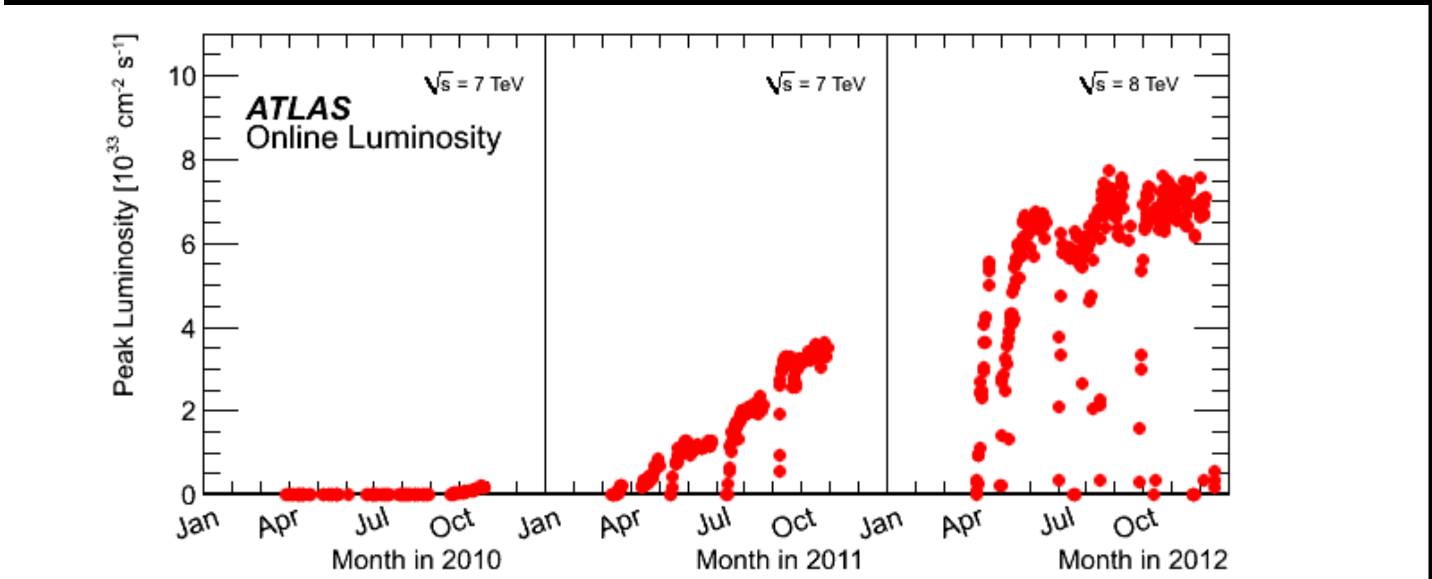




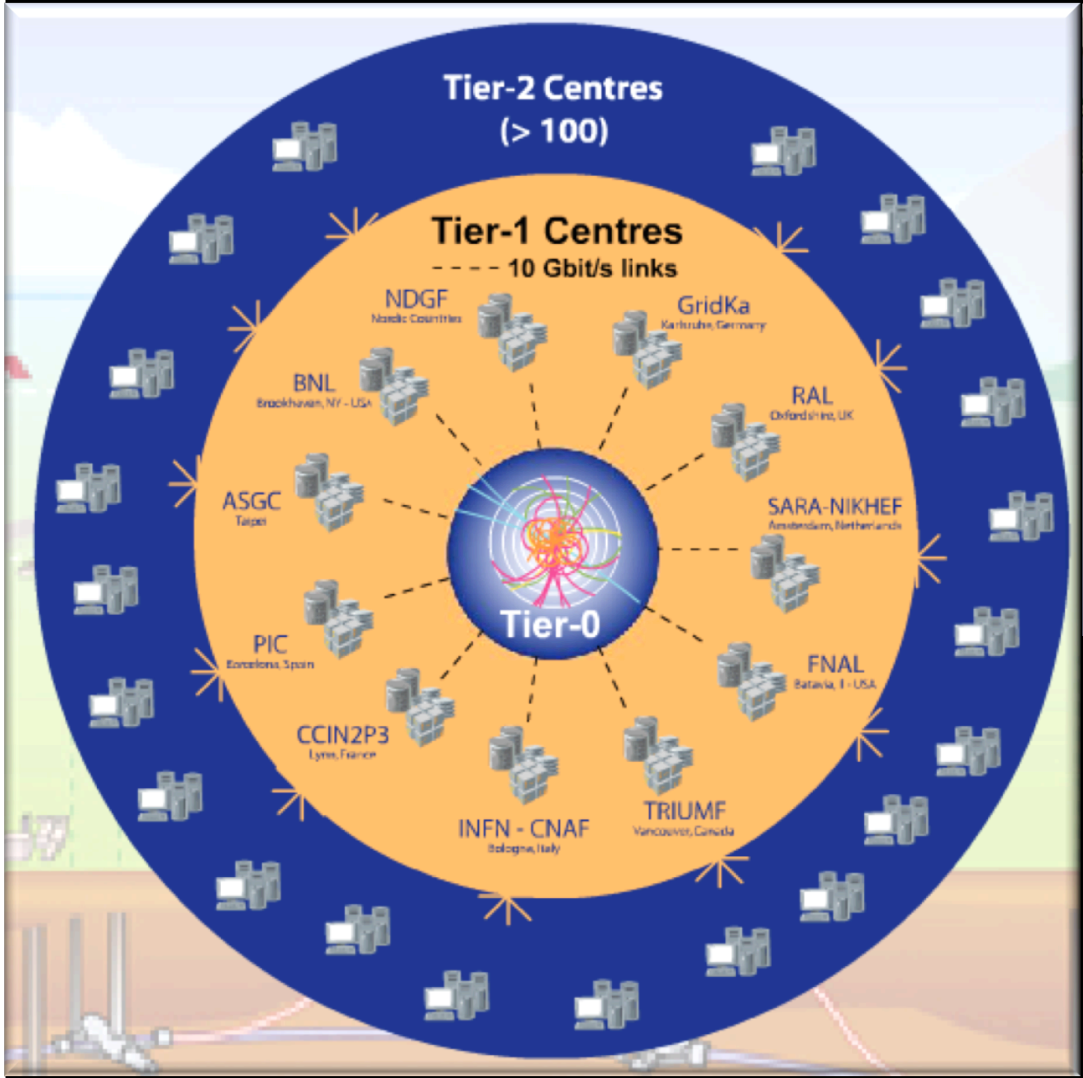
LHC Data Taking: 2010-2012



- Integrated L: 28 fb^{-1}
  - More than 2 x $L_{Tevatron}$
- Peak L: 7.7x1034 cm-2s-1
  - 20 million events/second
  - Write to disk about 400 events/s
- Data Volume
  - Total: ~150,000 TB

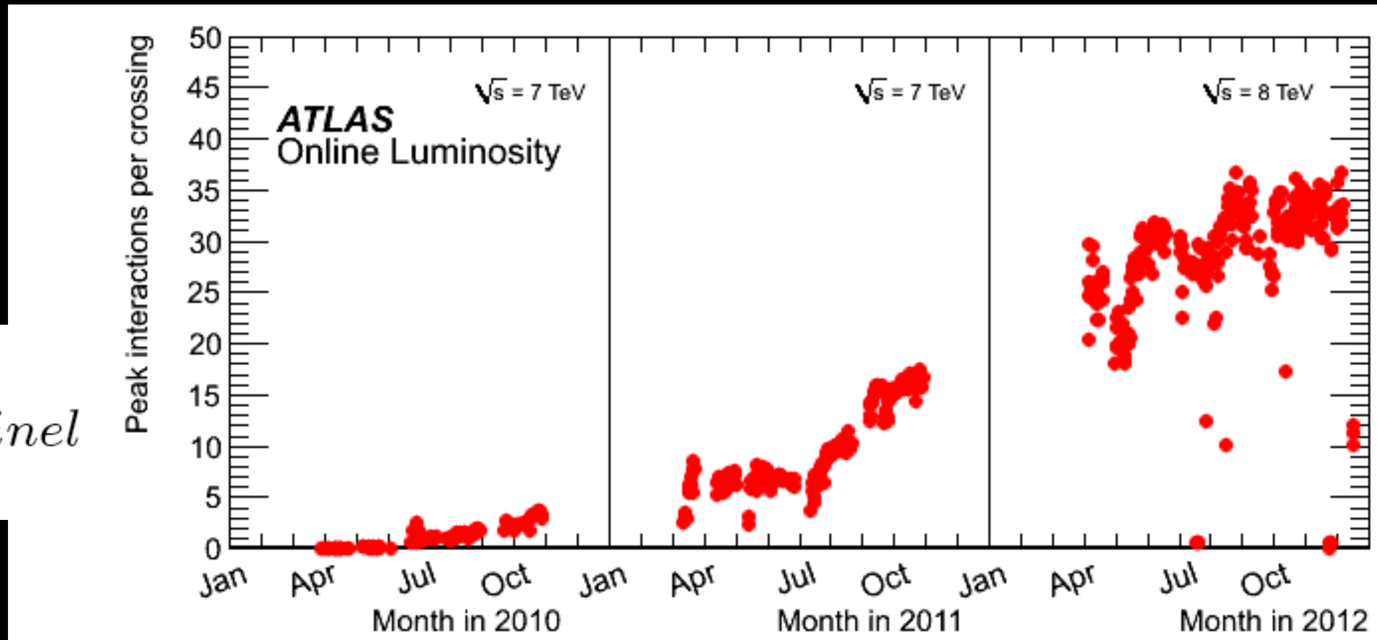


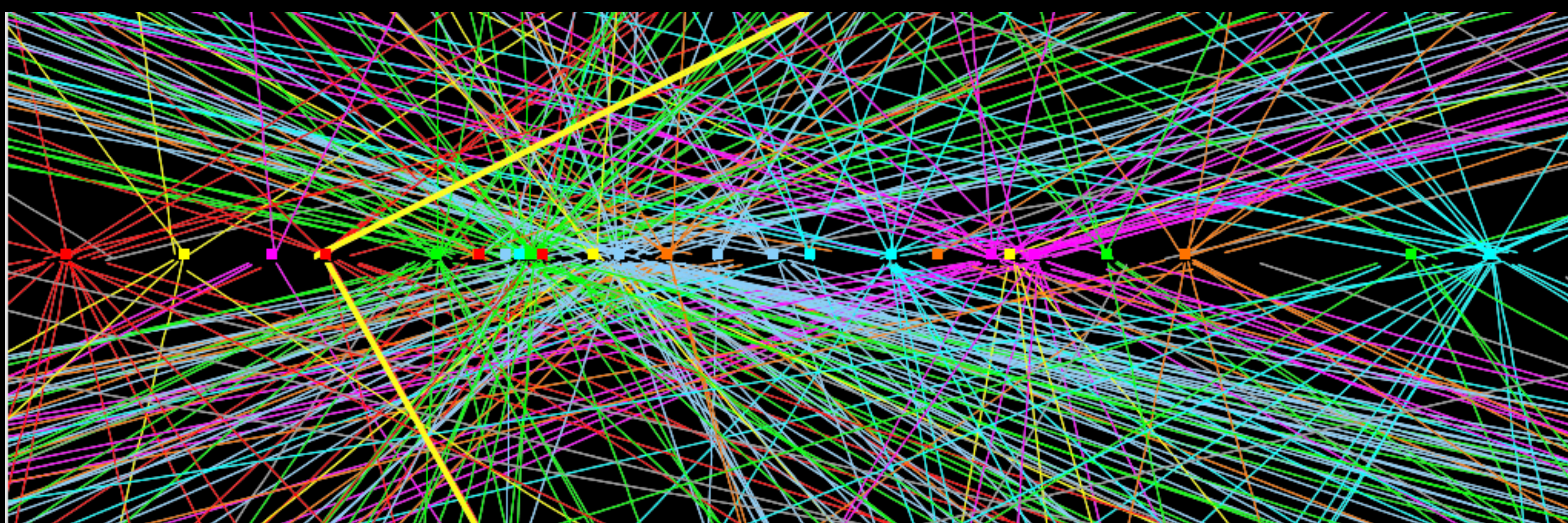
Worldwide LHC Computing Grid



The Price for high Luminosity: Pileup

$$\mu = \frac{n_1 n_2}{2\pi \Sigma_x \Sigma_y} \sigma_{inel}$$





Luminosity

- Single most important quantity
  - Drives our ability to detect new processes

$$L = \frac{f_{rev}\, n_{bunch}\, N_p^{\,2}}{4\pi\sigma_x\sigma_y}$$

revolving frequency: f_{rev}=11254/s
#bunches: n_{bunch}=1368
#protons / bunch: $N_p = 1.5 \times 10^{11}$
Width of beams: $\sigma_x \approx \sigma_y \approx 15\ \mu m$

  - Rate of physics processes per unit time directly related:

$$N_{obs} = \int L dt \cdot \varepsilon \cdot \sigma$$

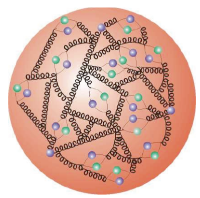
Cross section σ: Given by Nature (calc. by theorists)

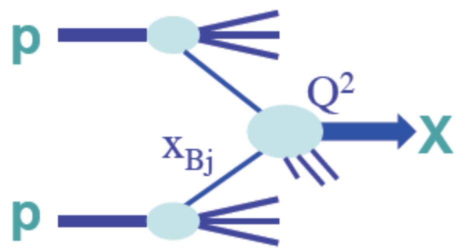
Efficiency: optimized by experimentalist

Ability to observe something depends on N_{obs}

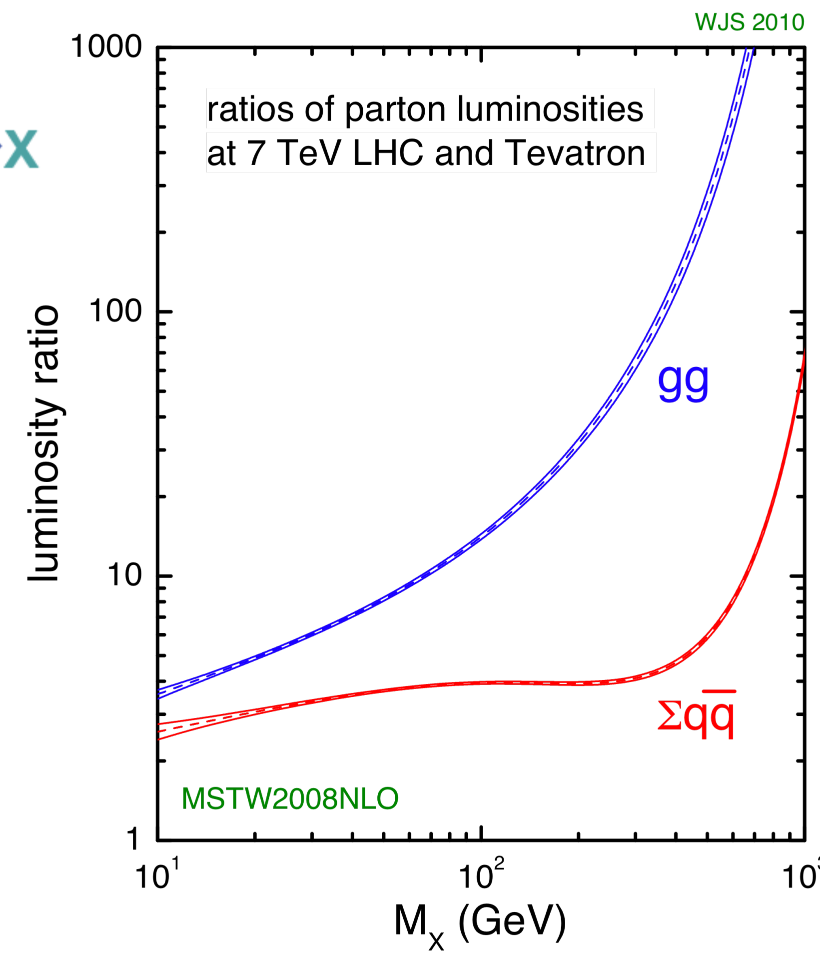
Physics Cross Sections

$$M_X = \sqrt{x_1 \cdot x_2 \cdot s}$$





Process	M_X	$\frac{\sigma(\text{LHC @ 7 TeV})}{\sigma(\text{Tevatron})}$
$q\bar{q} \rightarrow W$	80 GeV	3
$q\bar{q} \rightarrow Z'_{SM}$	1 TeV	50
$gg \rightarrow H$	120 GeV	20
$q\bar{q}/gg \rightarrow t\bar{t}$	2x173 GeV	15
$gg \rightarrow \tilde{g}\tilde{g}$	2x400 GeV	1000



- $\int Ldt = 1\ fb^{-1}$ at LHC competitive with 10 fb^{-1} at Tevatron for many processes

Calculating a Cross Section

- Cross section is convolution of PDF's and Matrix Element

Physical cross section

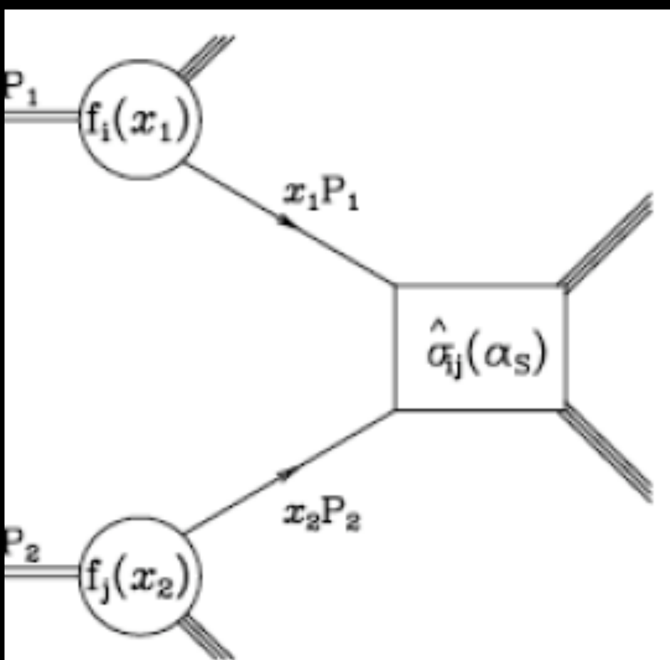
Parton distribution function

Renormalization scale μ_R

$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2\, f_i(x_1, \mu_F) f_j(x_2, \mu_F)\, \hat{\sigma}_{ij}(p_1, p_2, \alpha_S(\mu_R), Q^2, \mu_R, \mu_F).$$

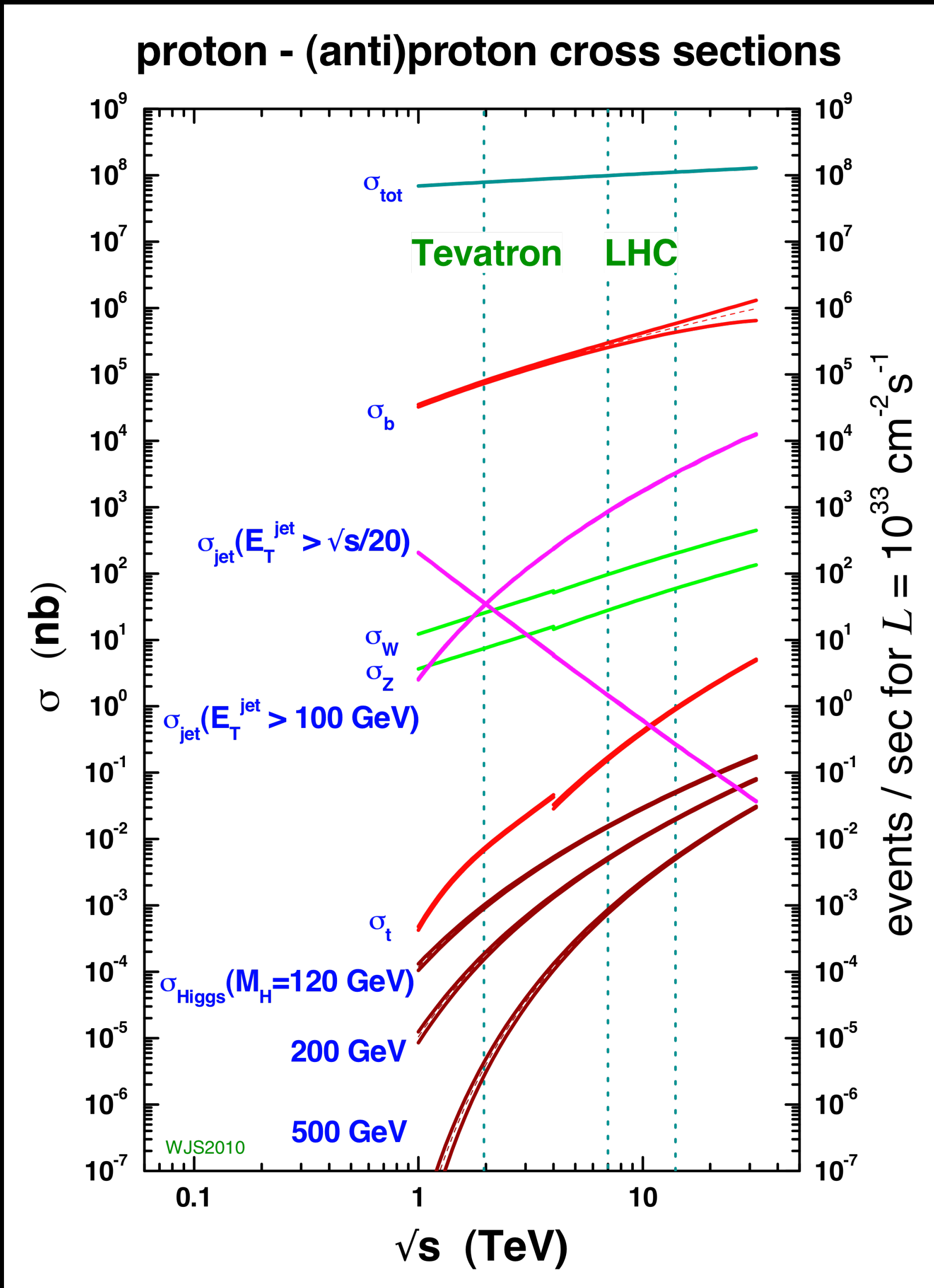
Factorization scale μ_F

Short distance cross section, calculated as a perturbation series in α_S



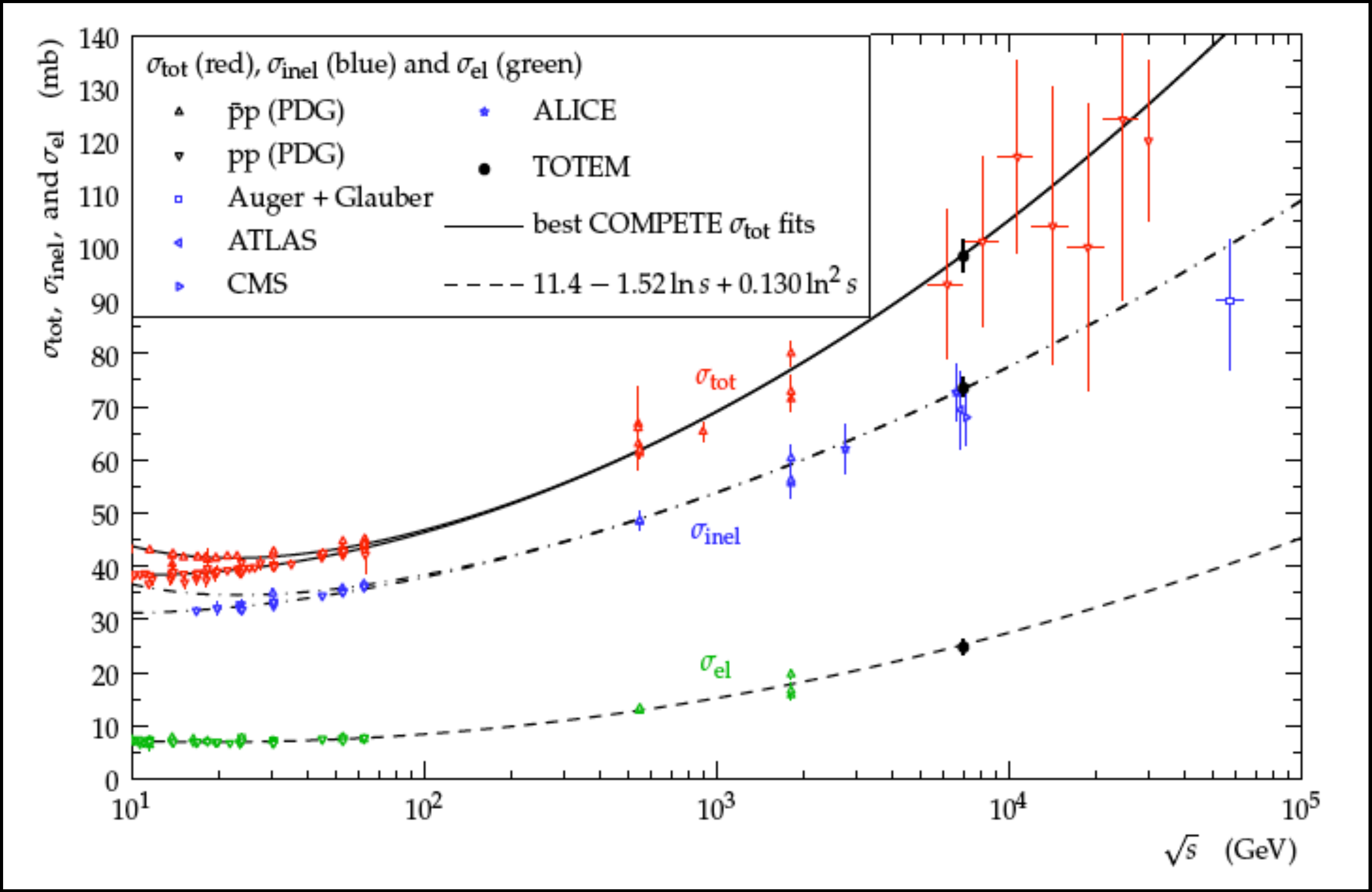
- Calculations are done in perturbative QCD
  - Possible due to factorization of ME and PDF's
    - Can be treated independently
  - Strong coupling (α_s) is large
    - Higher orders needed
    - Calculations complicated

Physics Processes at the LHC

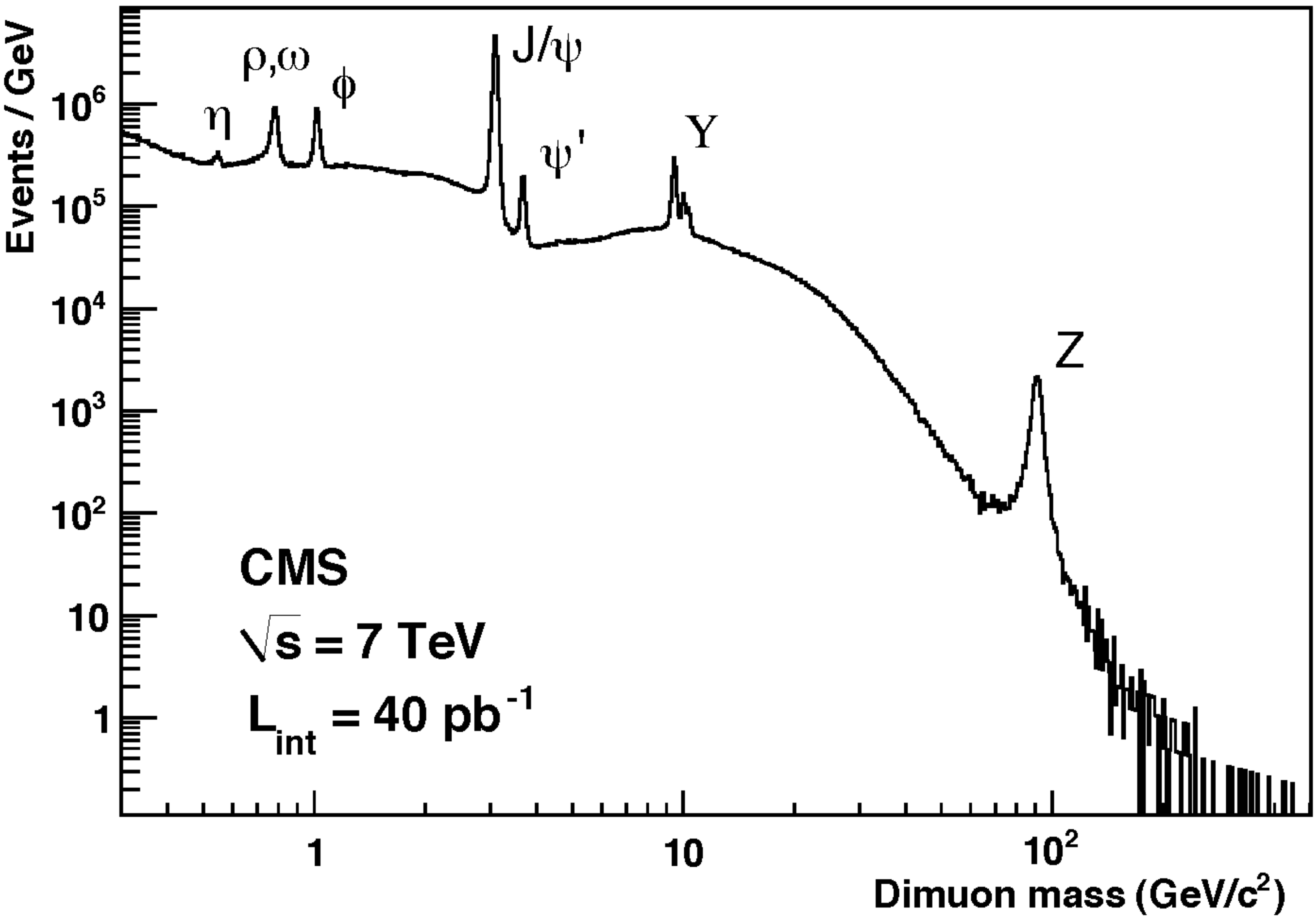


process	Rate at L_{peak} (Hz)
any interactions	10^9
Bottom quarks	10^6
Jets with p_T>100 GeV	10^4
W bosons	10^3
Z bosons	10^2
Top quarks	1
Higgs (M=125 GeV)	0.1
H->γγ (M=125 GeV)	2×10^{-4}

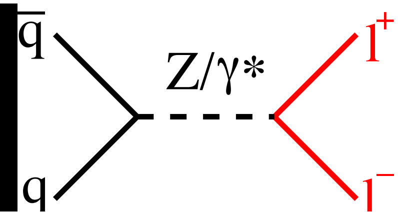
Total Cross Section: pp -> X



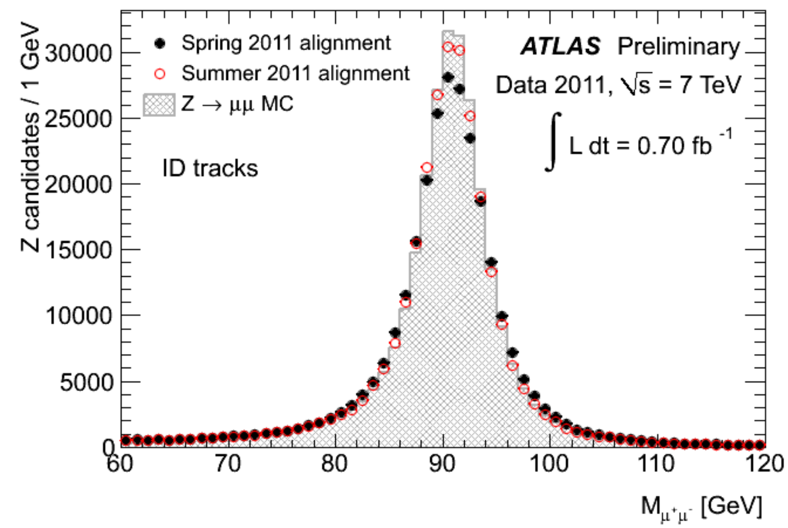
Dimuon Mass Spectrum

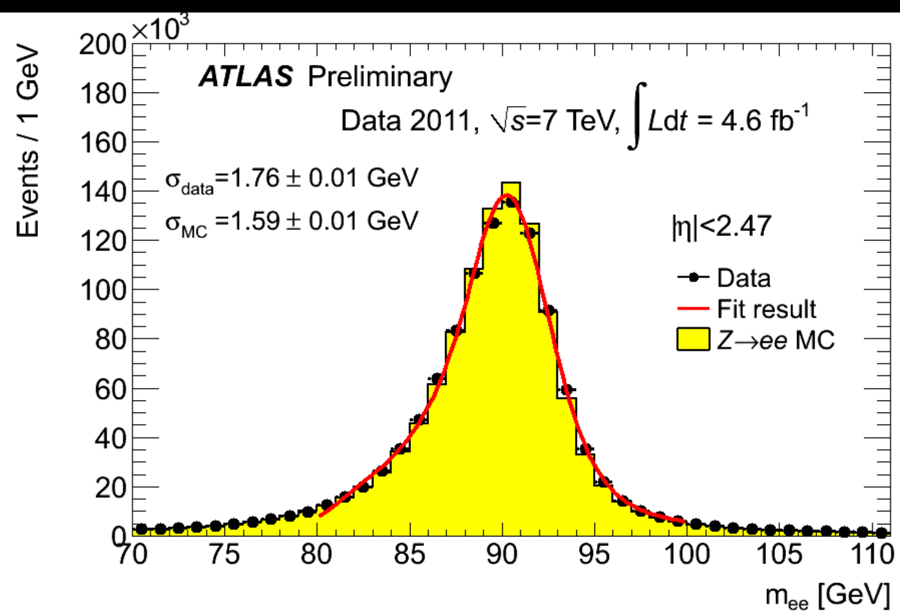


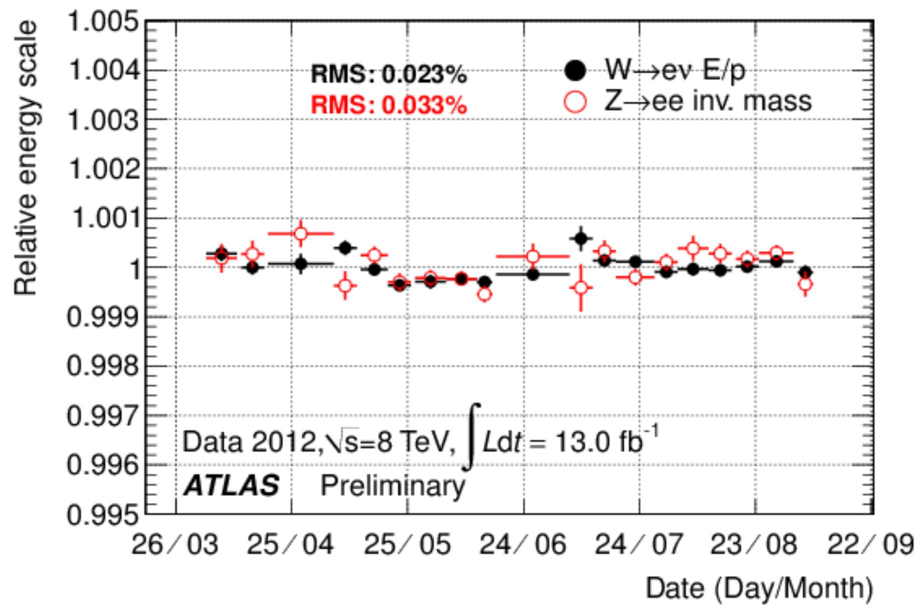
Z bosons



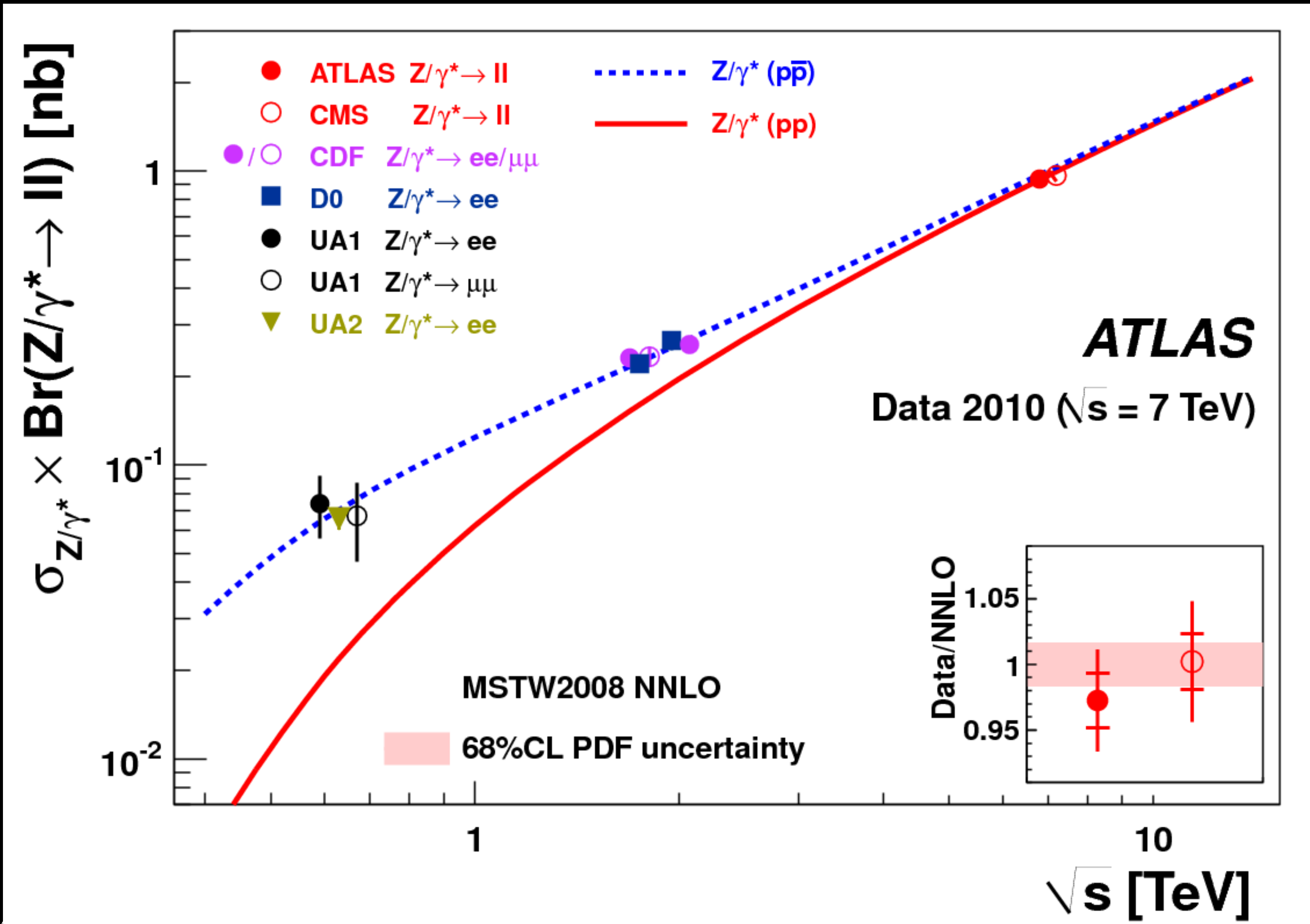
- Z boson used as calibration signal
  - electromagnetic calorimeter energy scale
  - muon momentum scale
  - many efficiencies
  - ….



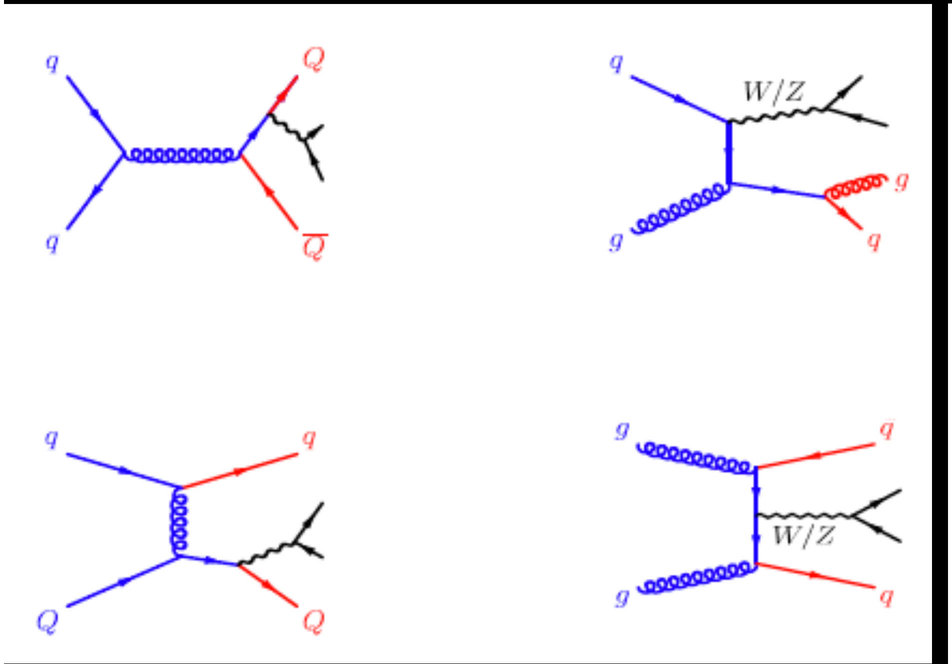


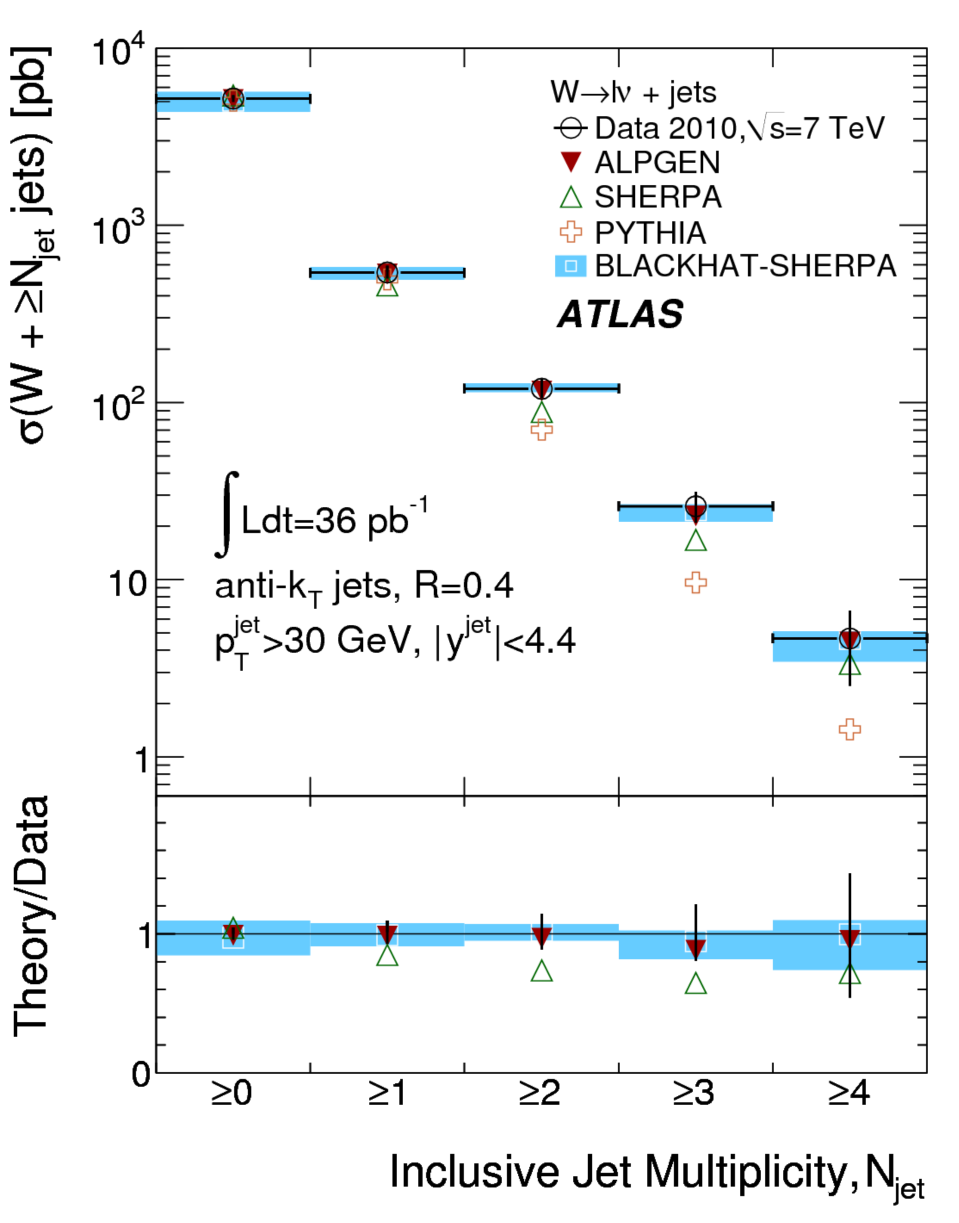


Z Boson Production



W+jets

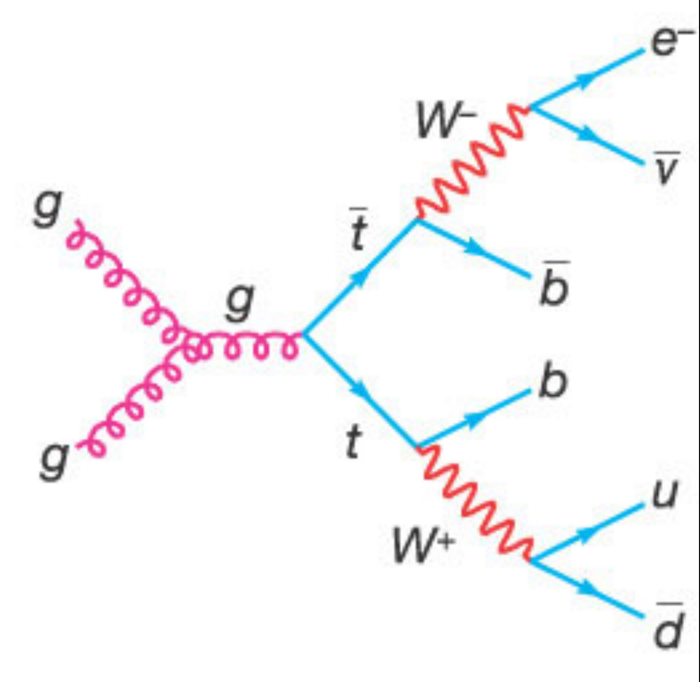




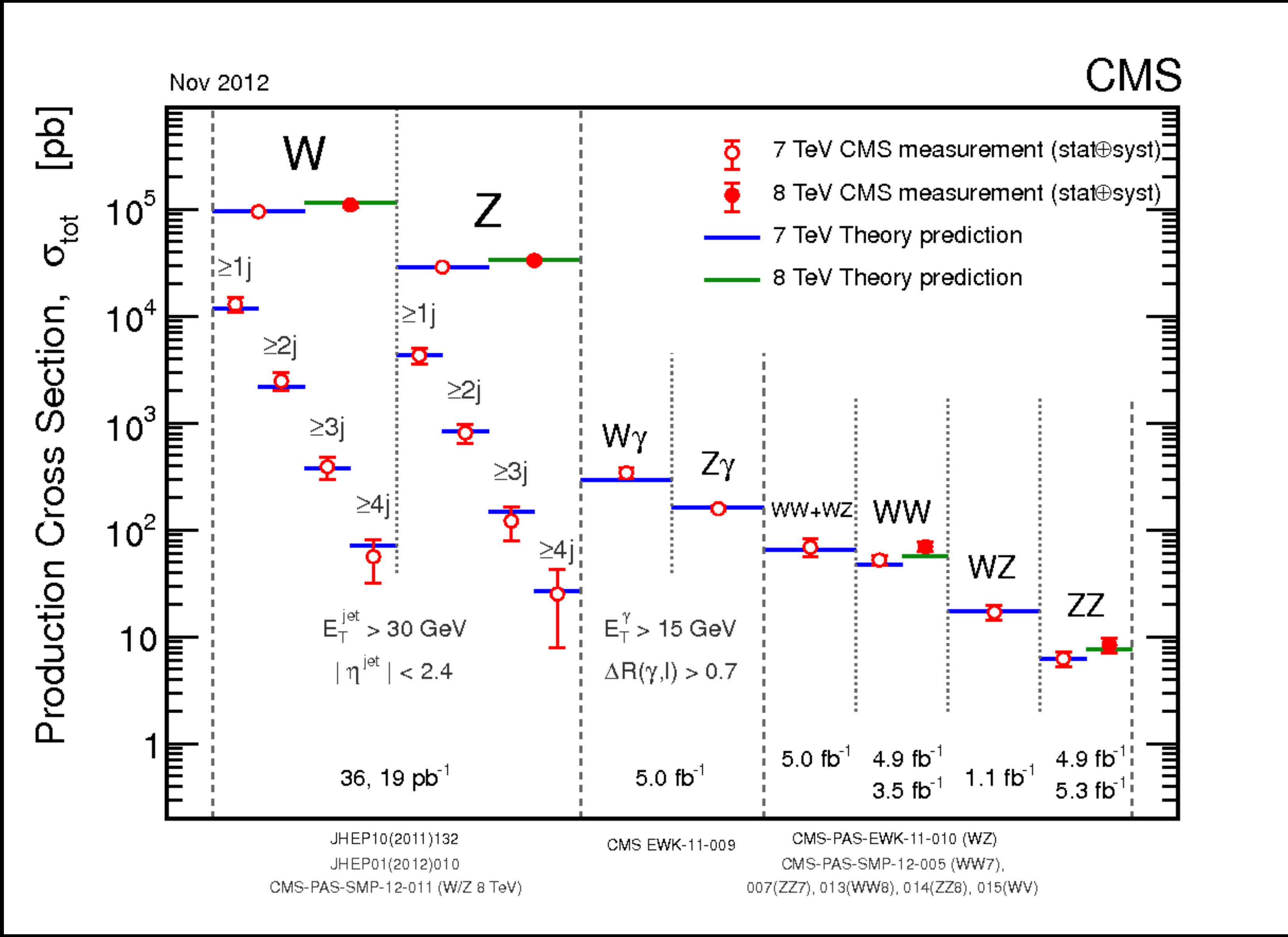
- Data agree with state of the art calculations (BLACKHAT+SHERPA)

L. Dixon *et al.*

Top Quark Production



Production of vector bosons and top quarks



The Higgs Boson Search

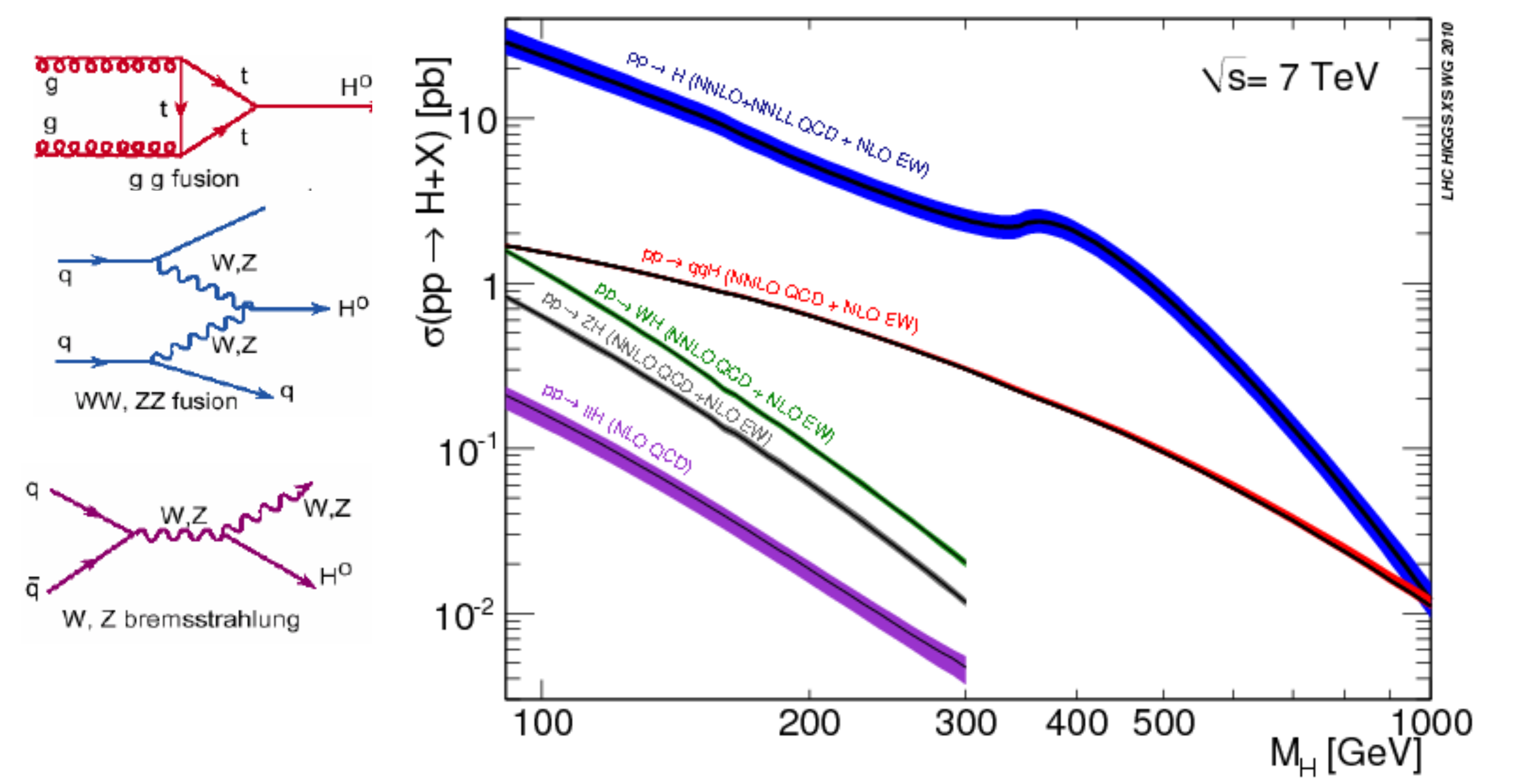
A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

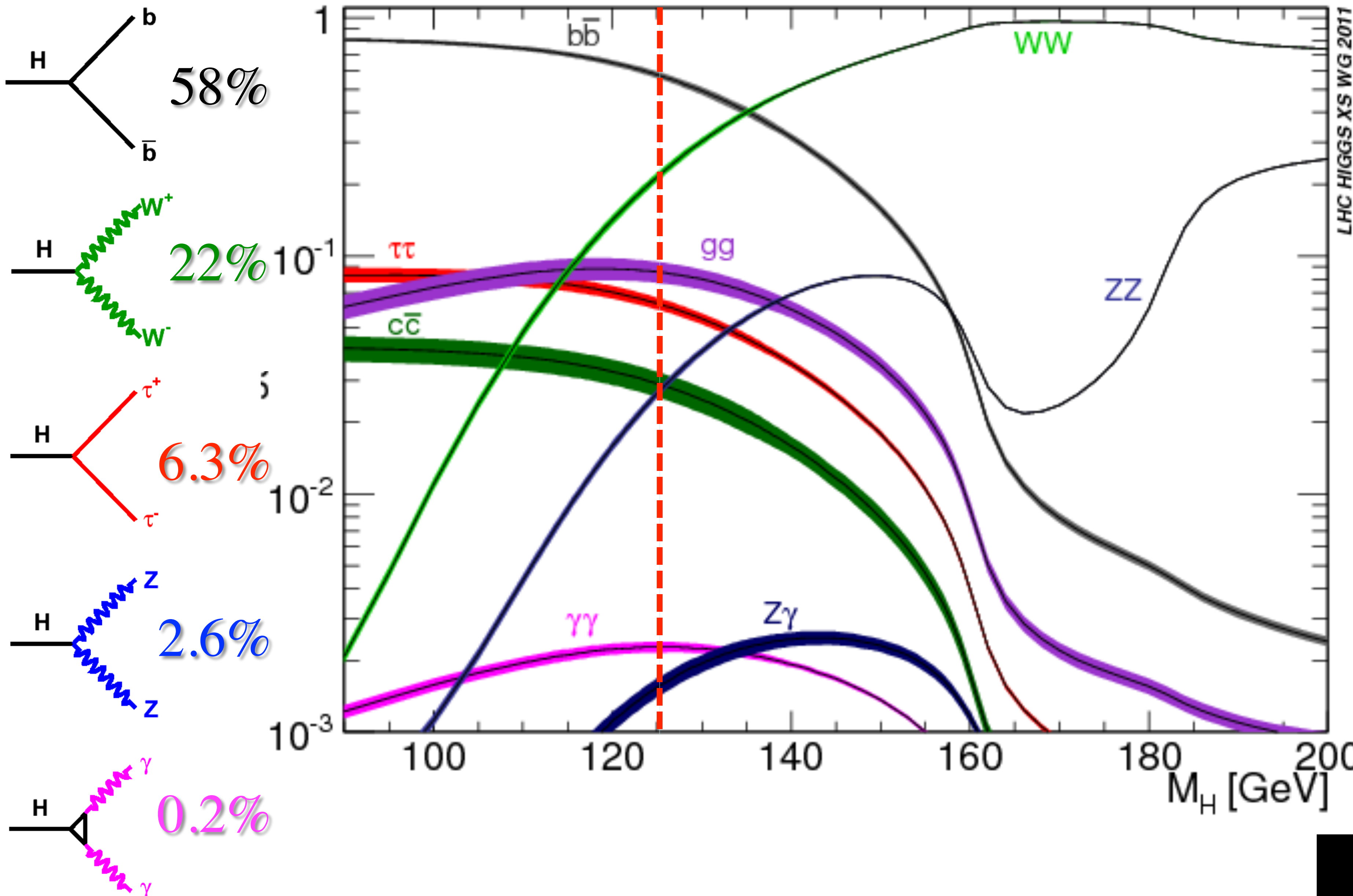
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Higgs Boson Production

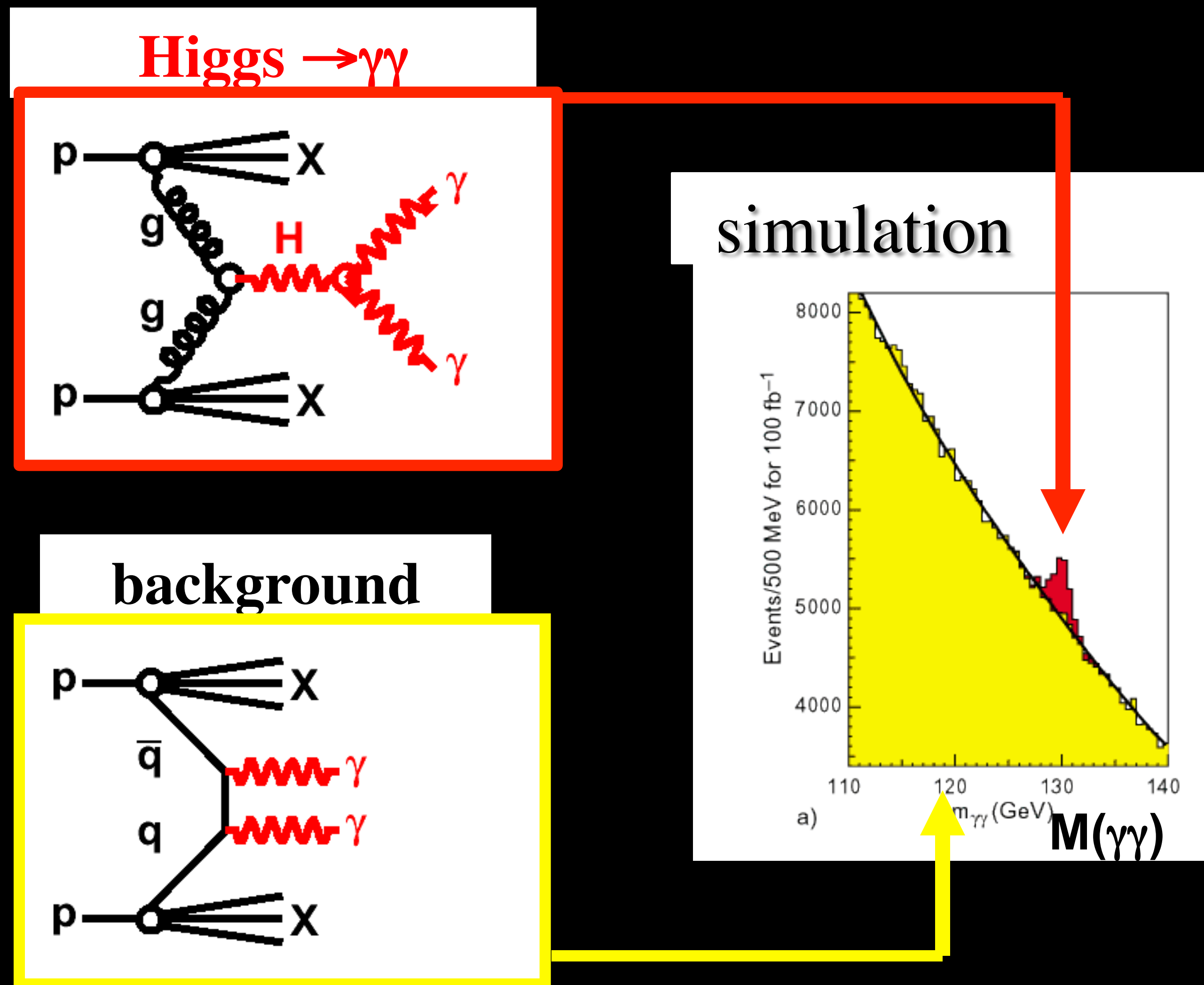


- Production rate know to ~10%
  – Various production mechanisms sensitive to different Higgs couplings (top quark versus W boson)

Higgs Boson Decay

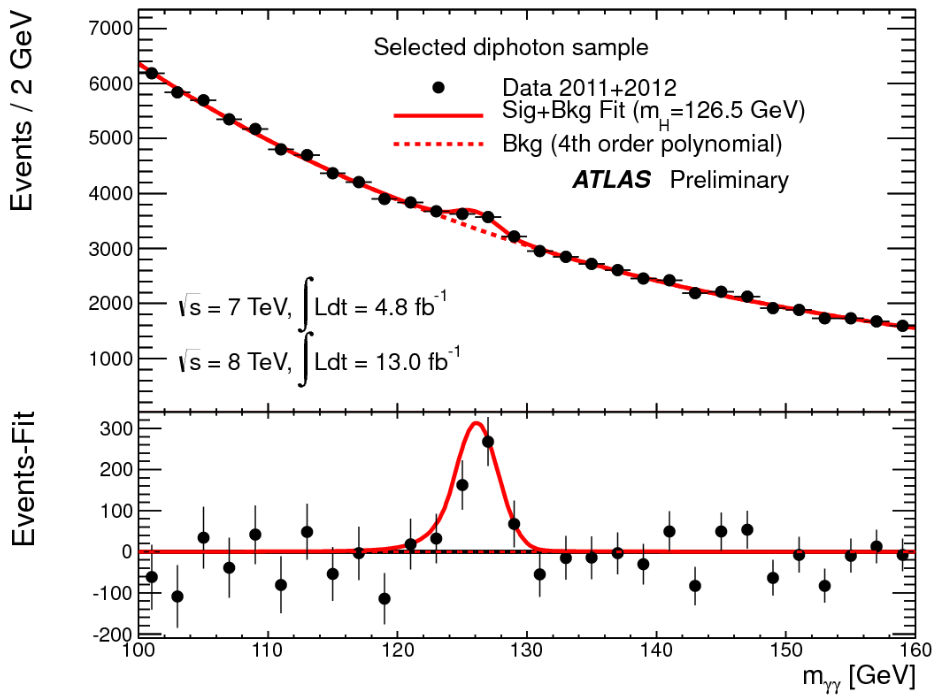


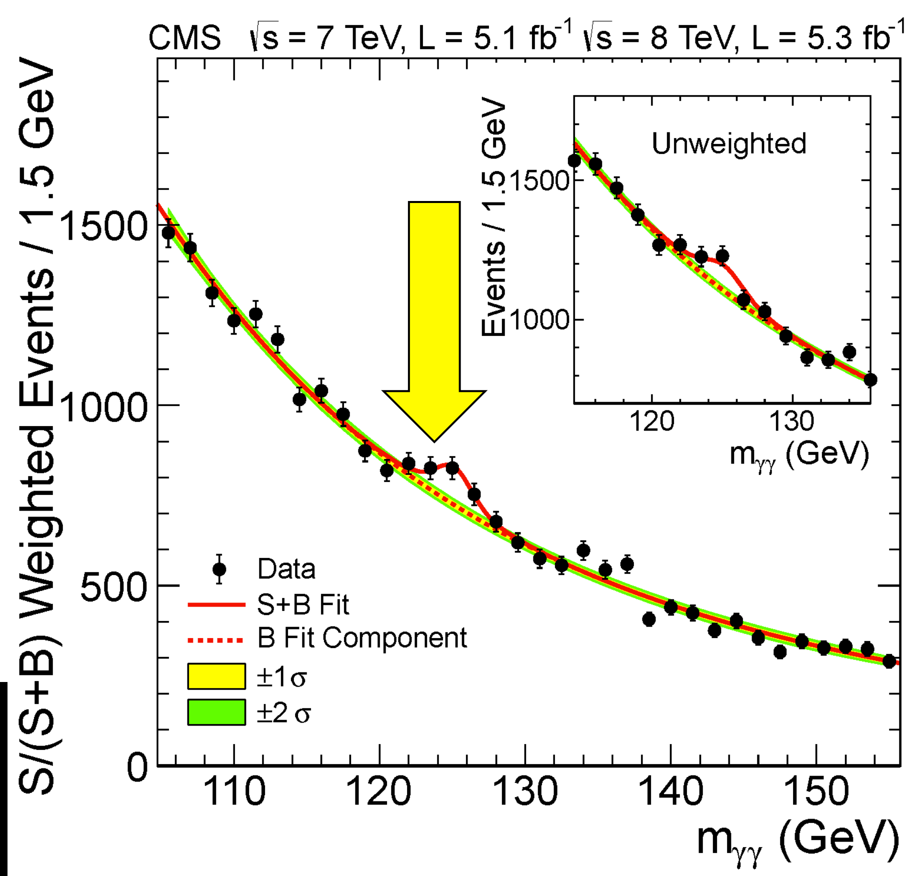
Finding the Higgs Boson (with photons)



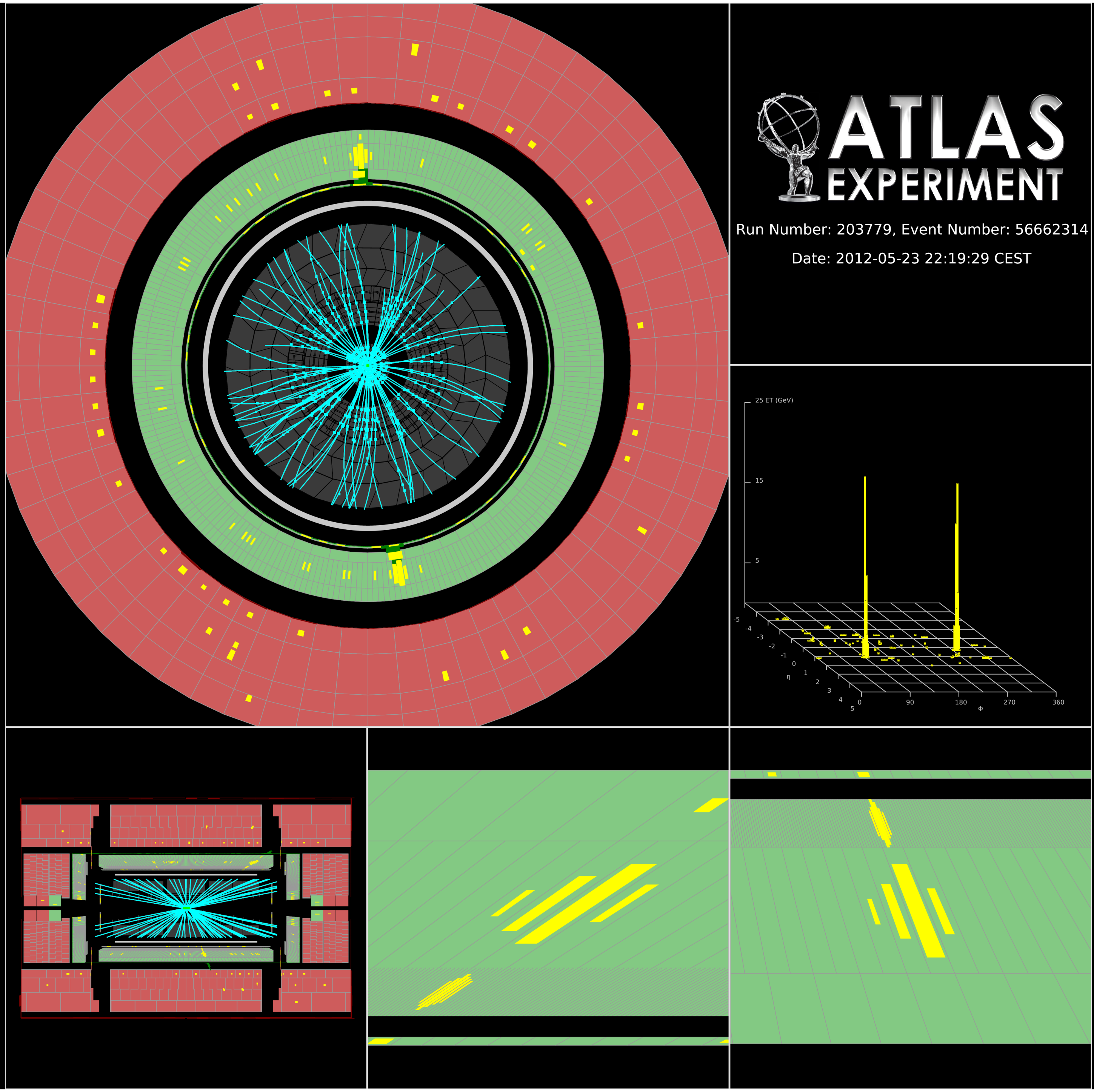
$$M_{Higgs} \approx M(\gamma\gamma) = 2\, E_1\, E_2\, (1-\cos\alpha)$$

Diphoton Mass Distributions

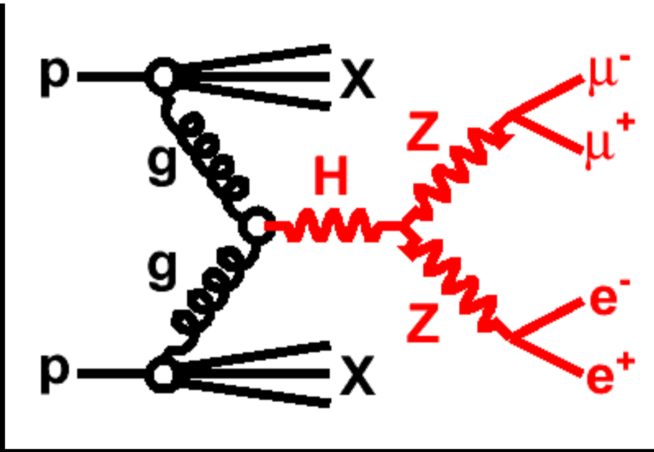


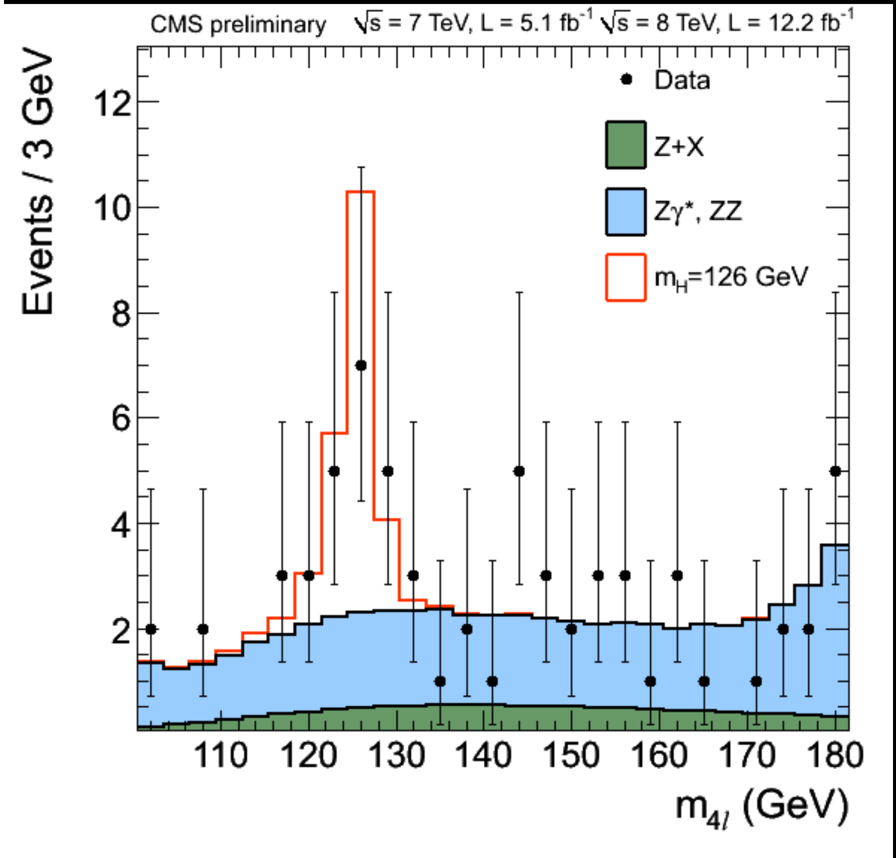


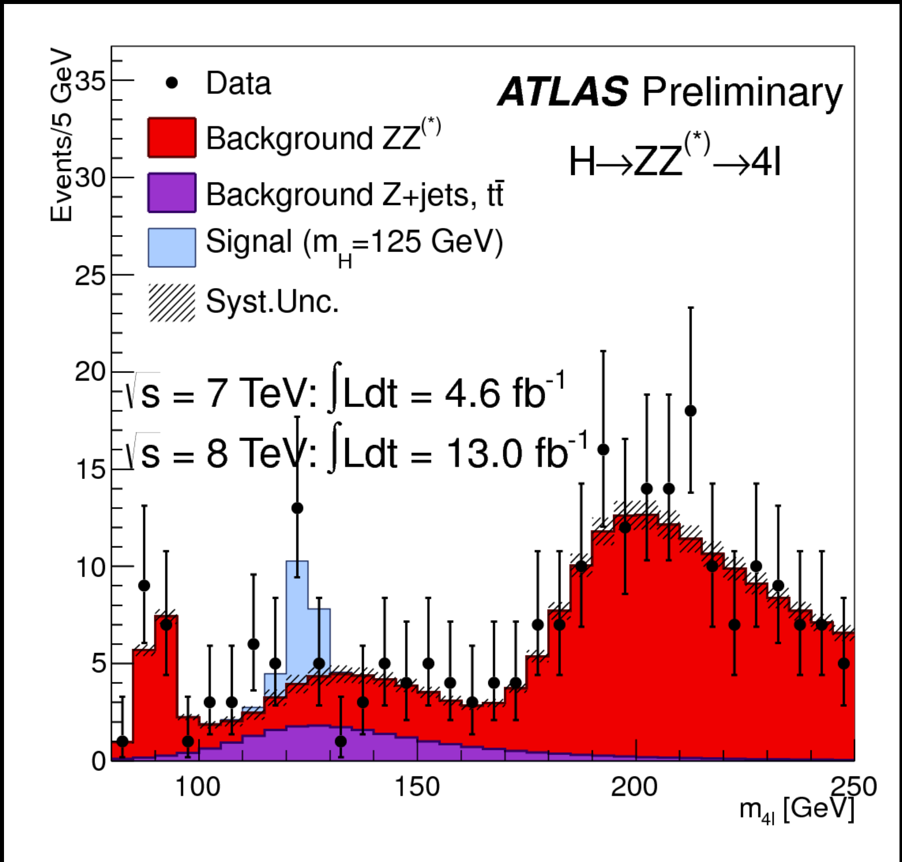
- Both experiments see peak at ~125 GeV

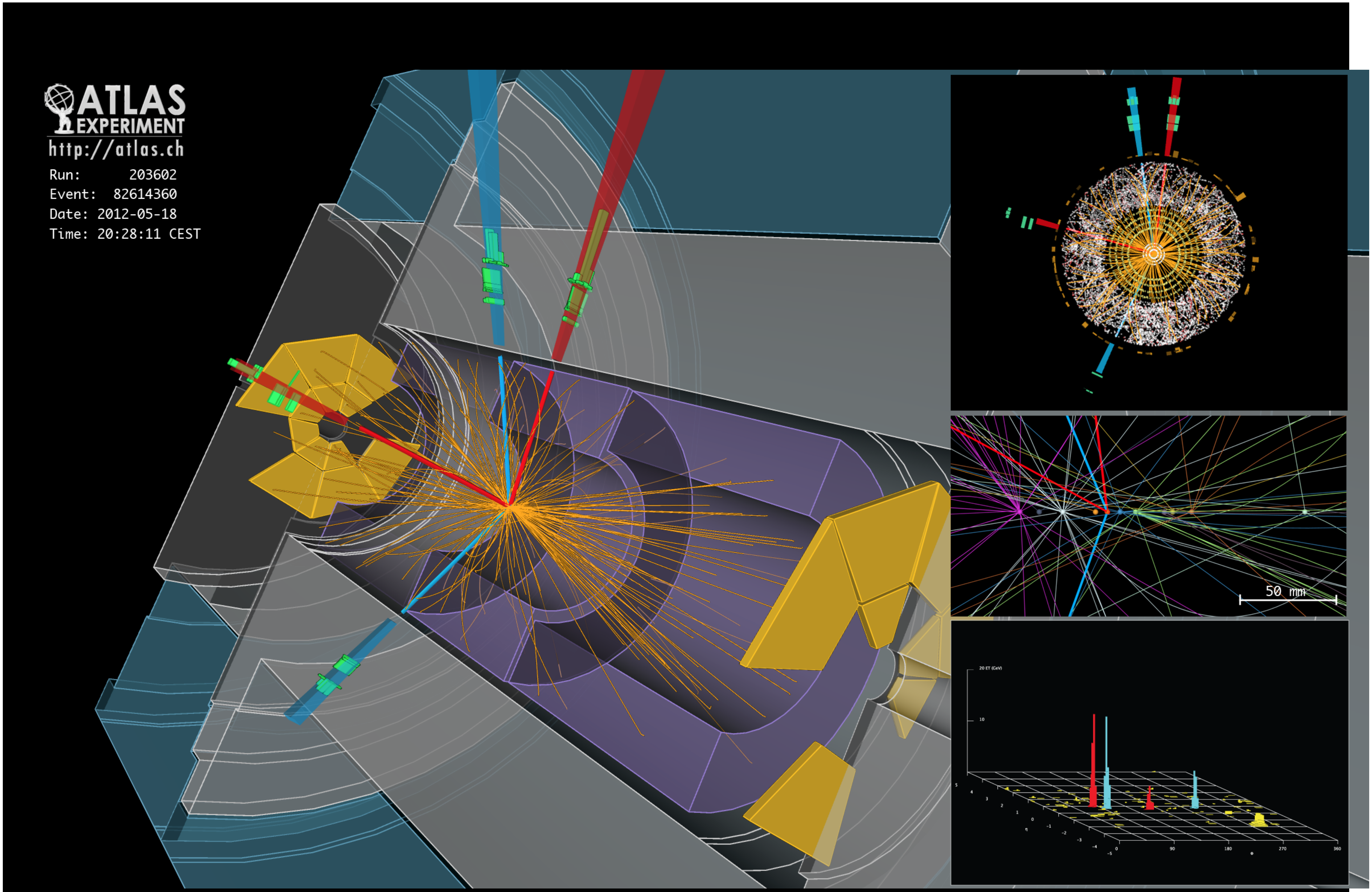

ATLAS
EXPERIMENT
Run Number: 203779, Event Number: 56662314
Date: 2012-05-23 22:19:29 CEST
25 ET (GeV)
15
5
-5
-4
-3
-2
-1
0
1
2
3
4
5
η
0
90
180
270
360
Φ

Higgs boson decaying to two Z bosons

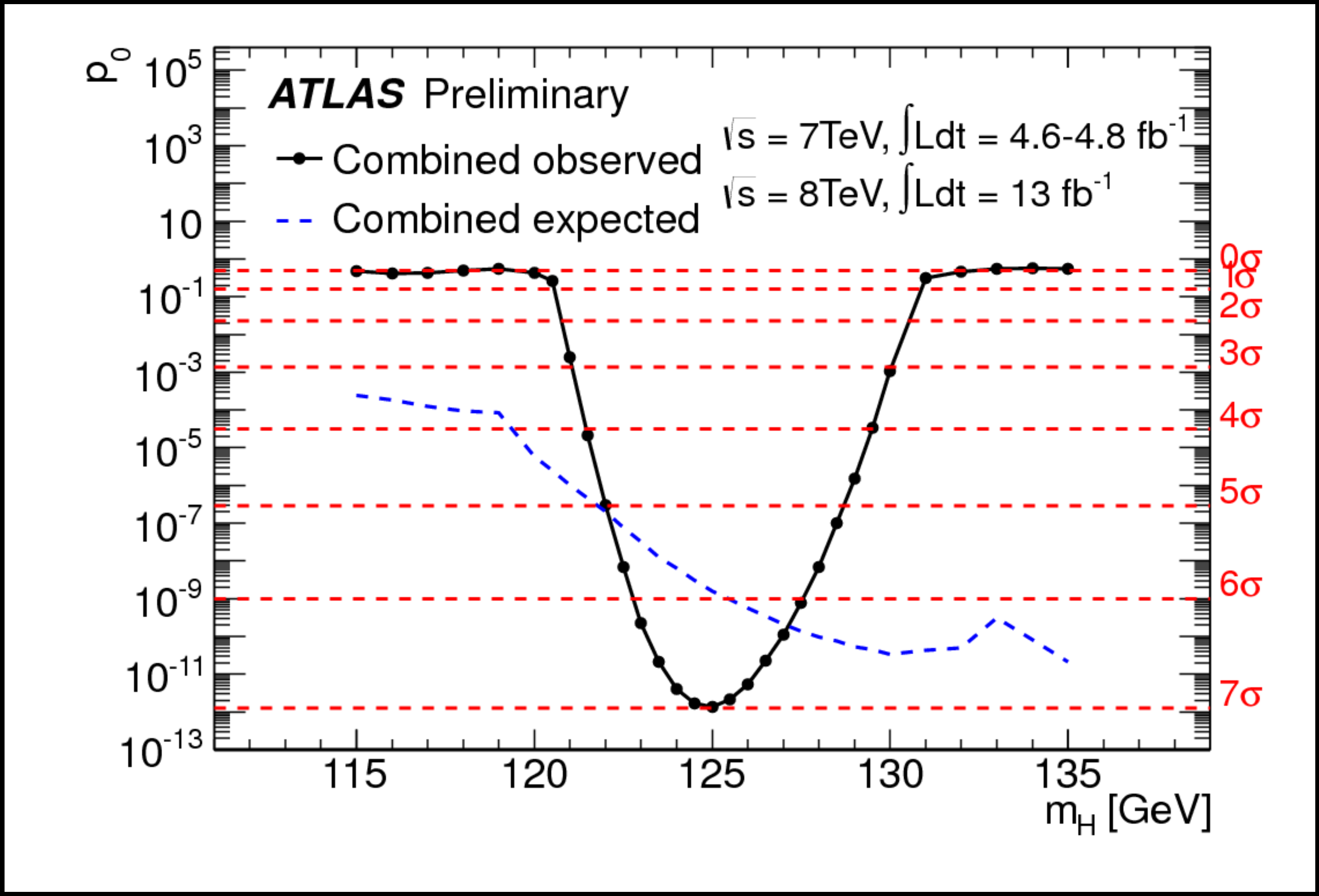






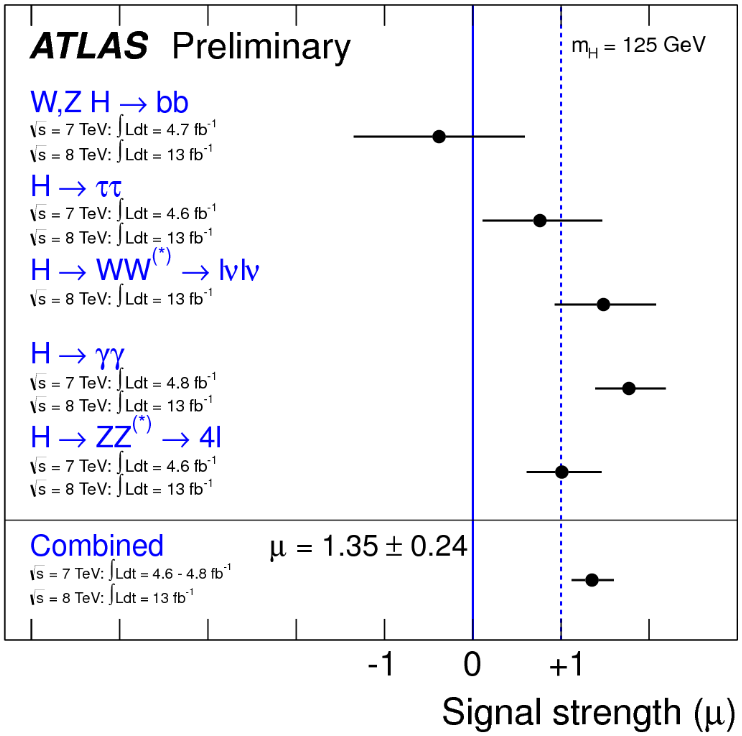

ATLAS EXPERIMENT
http://atlas.ch
Run: 203602
Event: 82614360
Date: 2012-05-18
Time: 20:28:11 CEST
50 mm

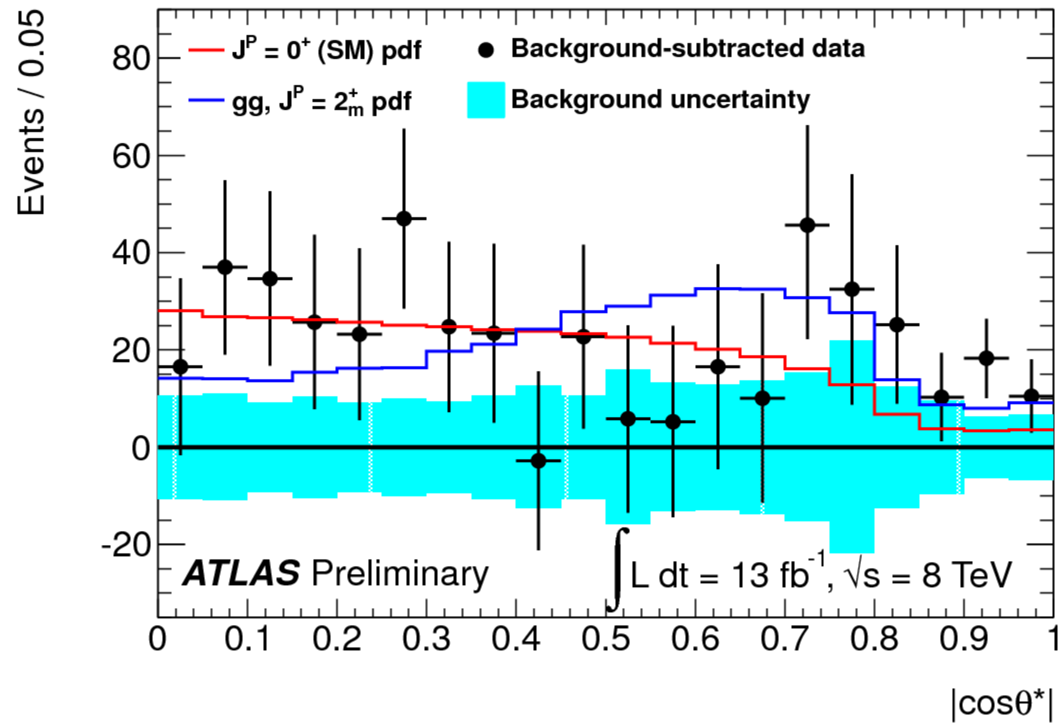
Probability of statistical fluctuation



- $p<10^{-11}$ corresponding to about 7σ

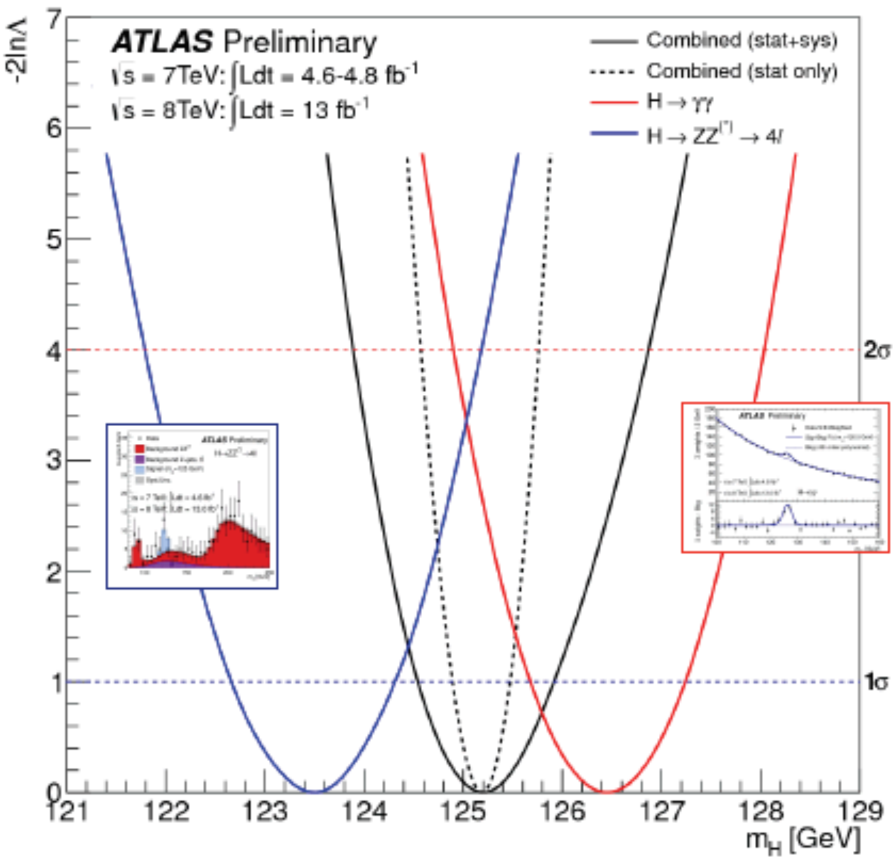
Is it the Standard Model Higgs boson?

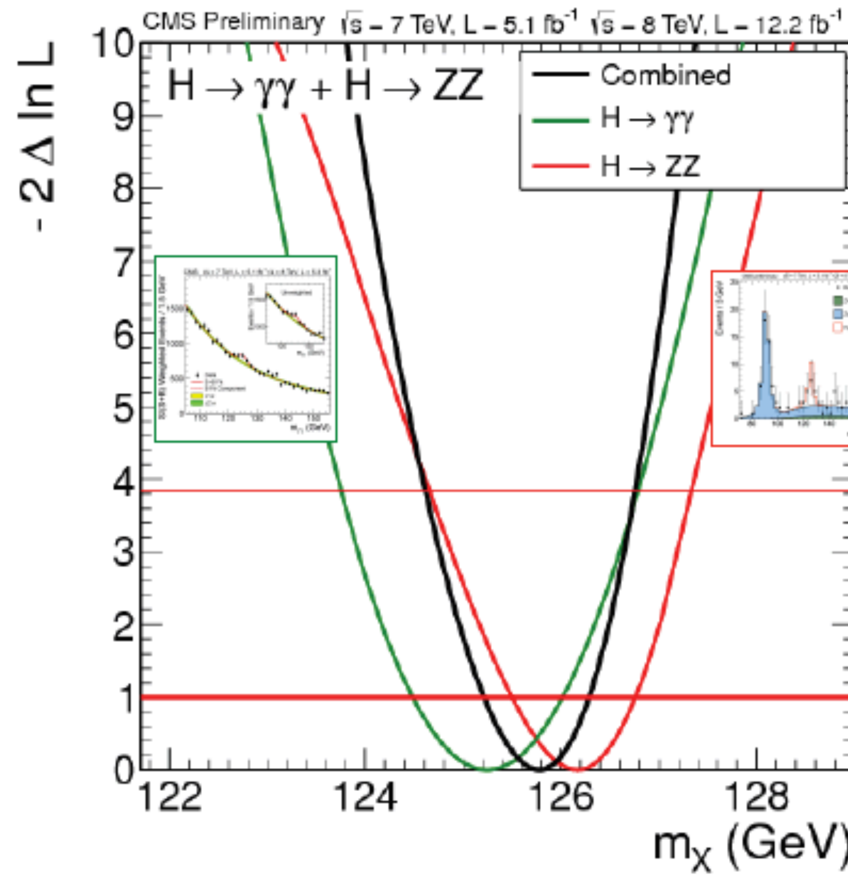




- Decay rates, spin and parity consistent with SM Higgs boson
  - But statistics low
  - Need much more data to probe thoroughly

Mass Measurement

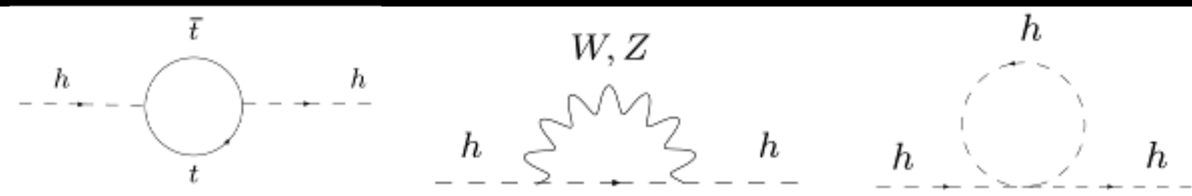




ATLAS: $M_H = 125.2 \pm 0.3_{stat} \pm \mathbf{0.6}_{sys}$ GeV

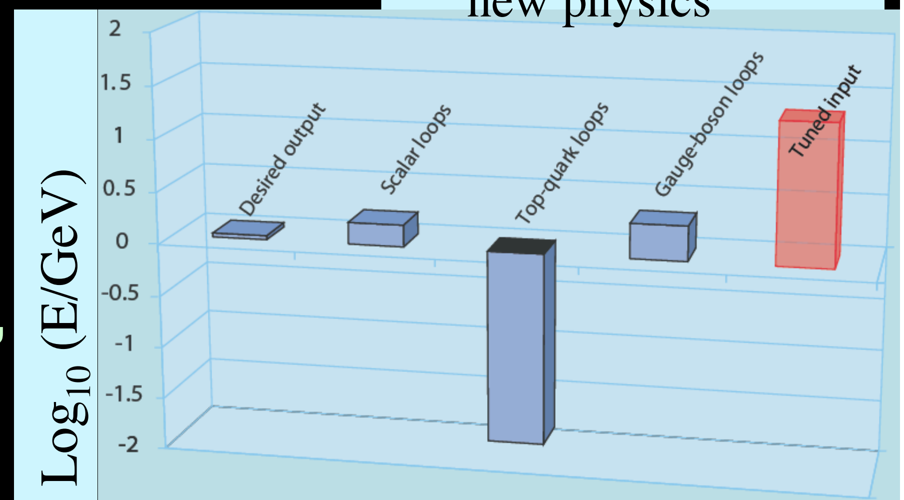
CMS: $M_H = 125.8 \pm 0.4_{stat} \pm \mathbf{0.4}_{sys}$ GeV

Hierarchy Problem



$m^2_H \approx (200\ \mathrm{GeV})^2 = m^2_H{}^{tree} + \delta\, m^2_H{}^{top} + \delta\, m^2_H{}^{gauge} + \delta\, m^2_H{}^{higgs}$

$M_{\text{new physics}} = 5$ TeV



- Free parameter $m_H{}^{tree}$ "finetuned" to cancel huge corrections
- Considered to be "unnatural"
  - Some unknown ad-hoc parameter introduced with superb precision

Theoretically not satisfactory

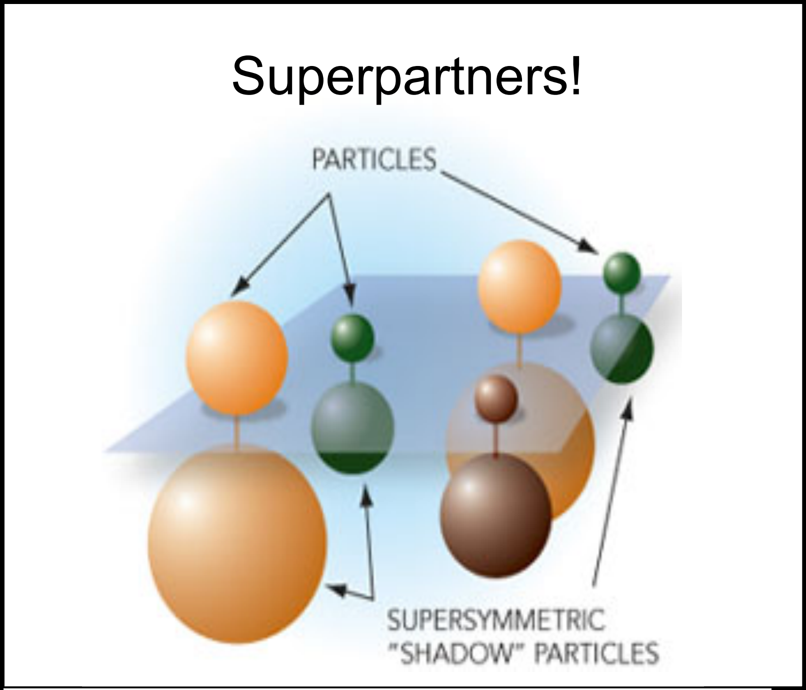
Solving the finetuning problem *Dimopoulos et al.*

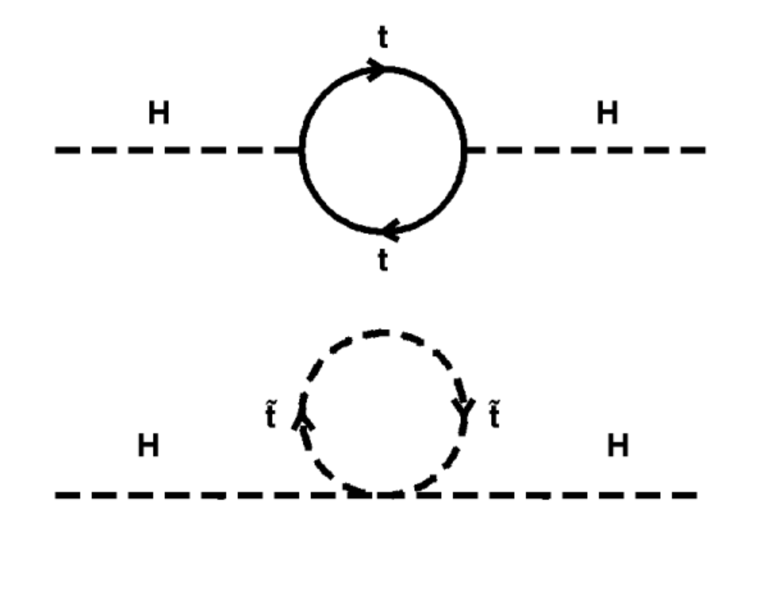
- "Supersymmetric" particles
  - Each SM particle has a partner with different spin, e.g.:

SM	spin	SUSY	spin
electron	1/2	selectron	0
top	1/2	stop	0
gluon	1	gluino	1/2

  - SUSY loops cancel SM loops
    - Size of loops naturally the same IF particle masses similar

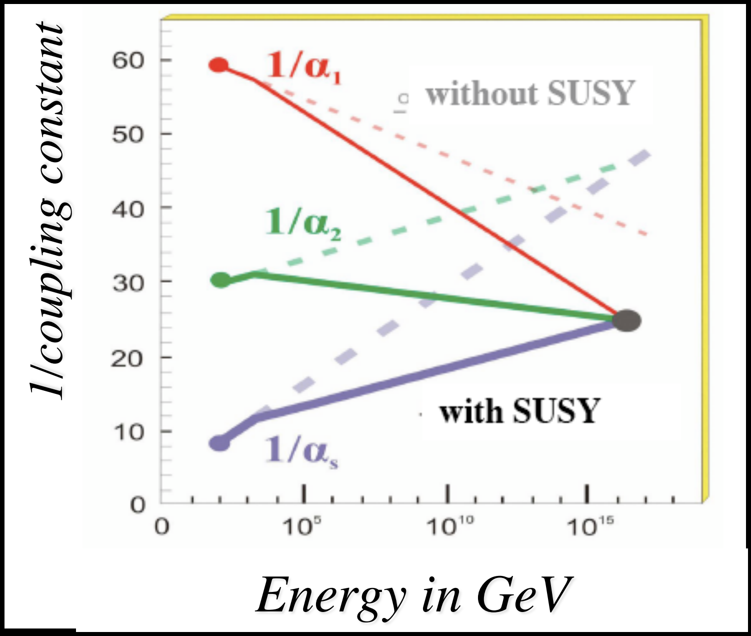
    => SUSY particles should be found at the LHC
  - No tuned ad-hoc parameter needed



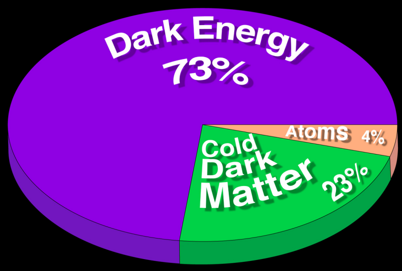


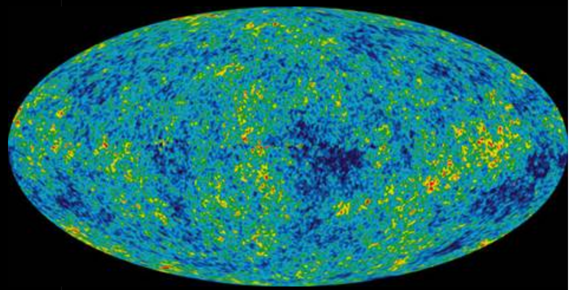
More virtues of Supersymmetry (SUSY)

- Electromagnetic, strong and weak force unify!
  - Miss unification in SM (barely)
  - Unify in SUSY if masses below ~100 TeV!



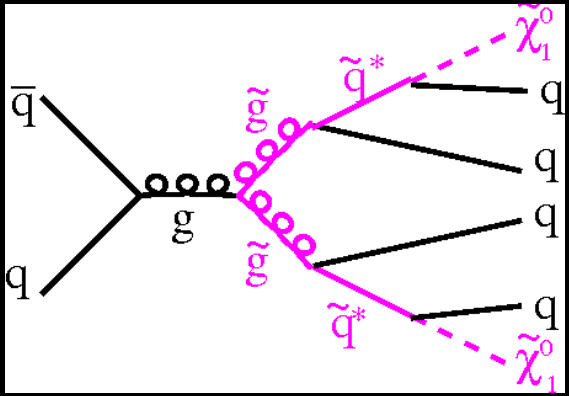
- Provides candidate for dark matter with mass ~ 0.1-1 TeV
  - Lightest SUSY particle, typically the "neutralino"



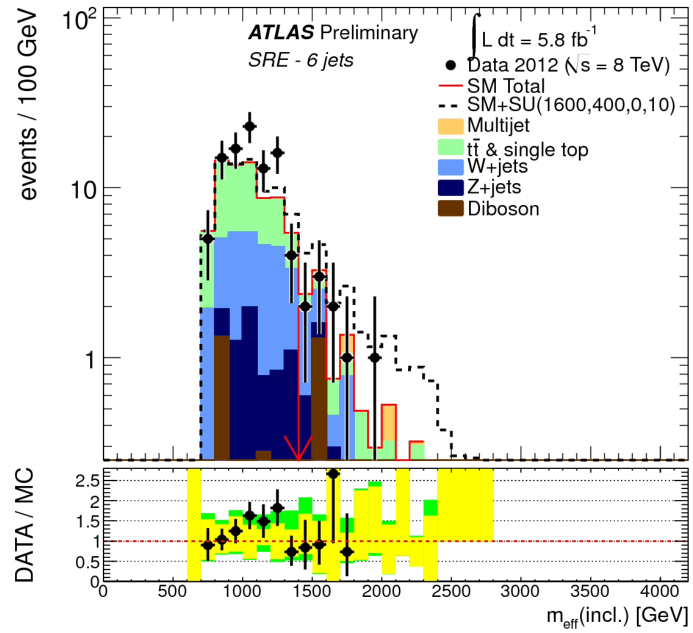


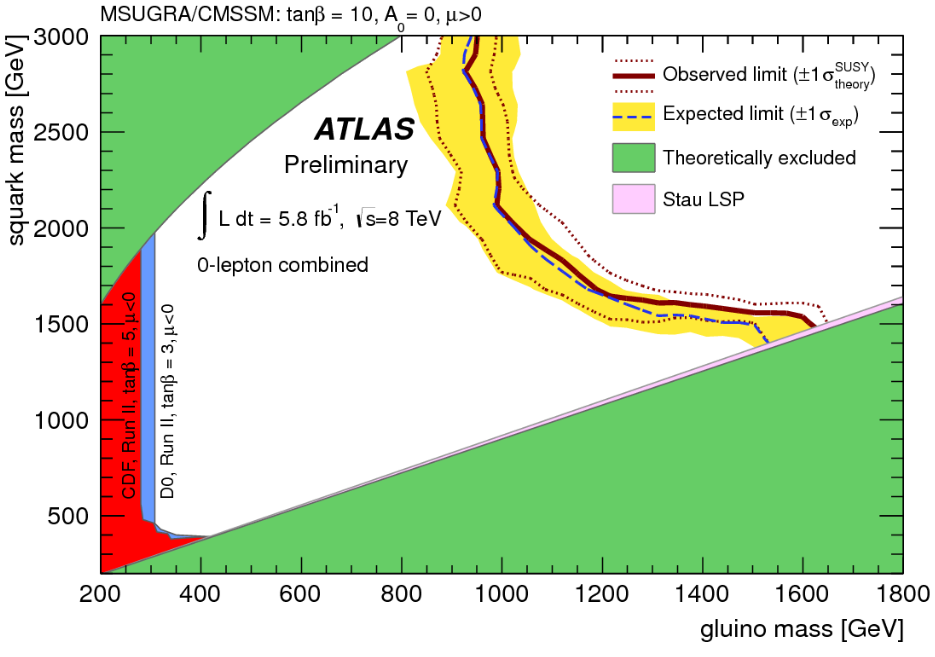
If SUSY particles are solution to finetuning problem they will be found at the LHC

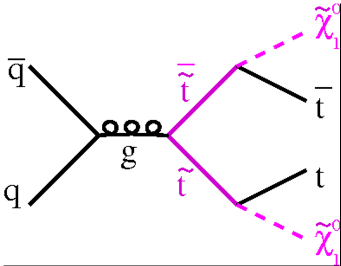
Current Result: Jets + MET



- Jets result from cascade decays of squarks and gluinos
- Excludes squarks with m<1.5 TeV and gluinos with m<1 TeV
  - Assuming the squarks are all approximately degenerate

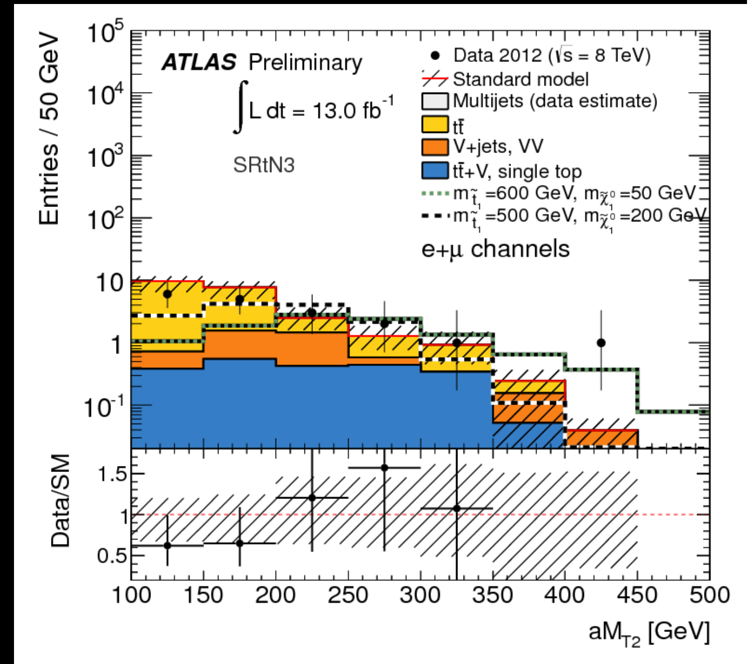


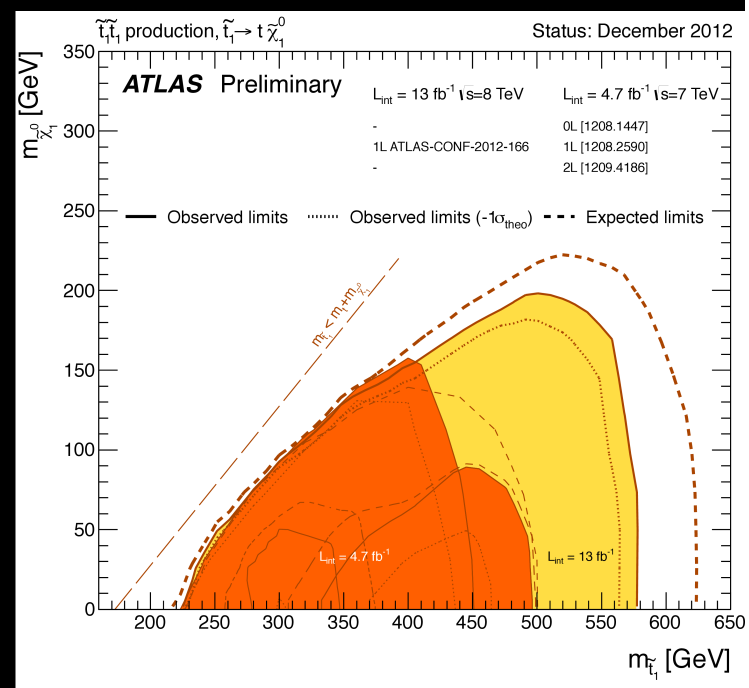




Top Squark

- top squark required to be light to solve hiearchy problem
- top squark search done in many decay channels
- M(stop)<550 GeV excluded for LSP masses below ~150 GeV
  - Many caveats though as statement depends on other SUSY parameters

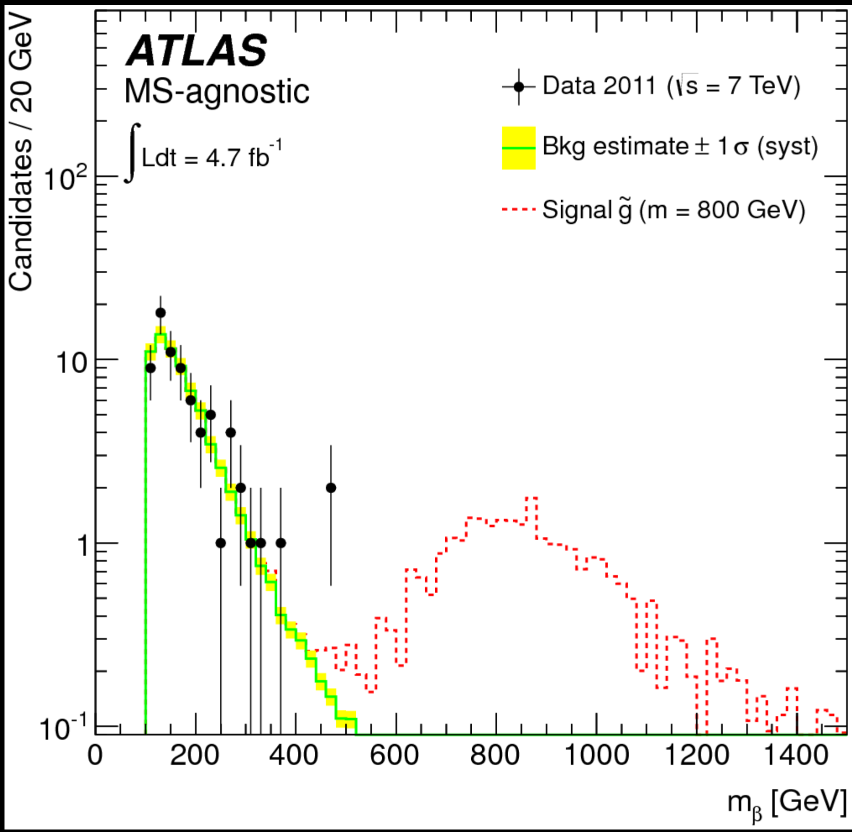




Split SUSY

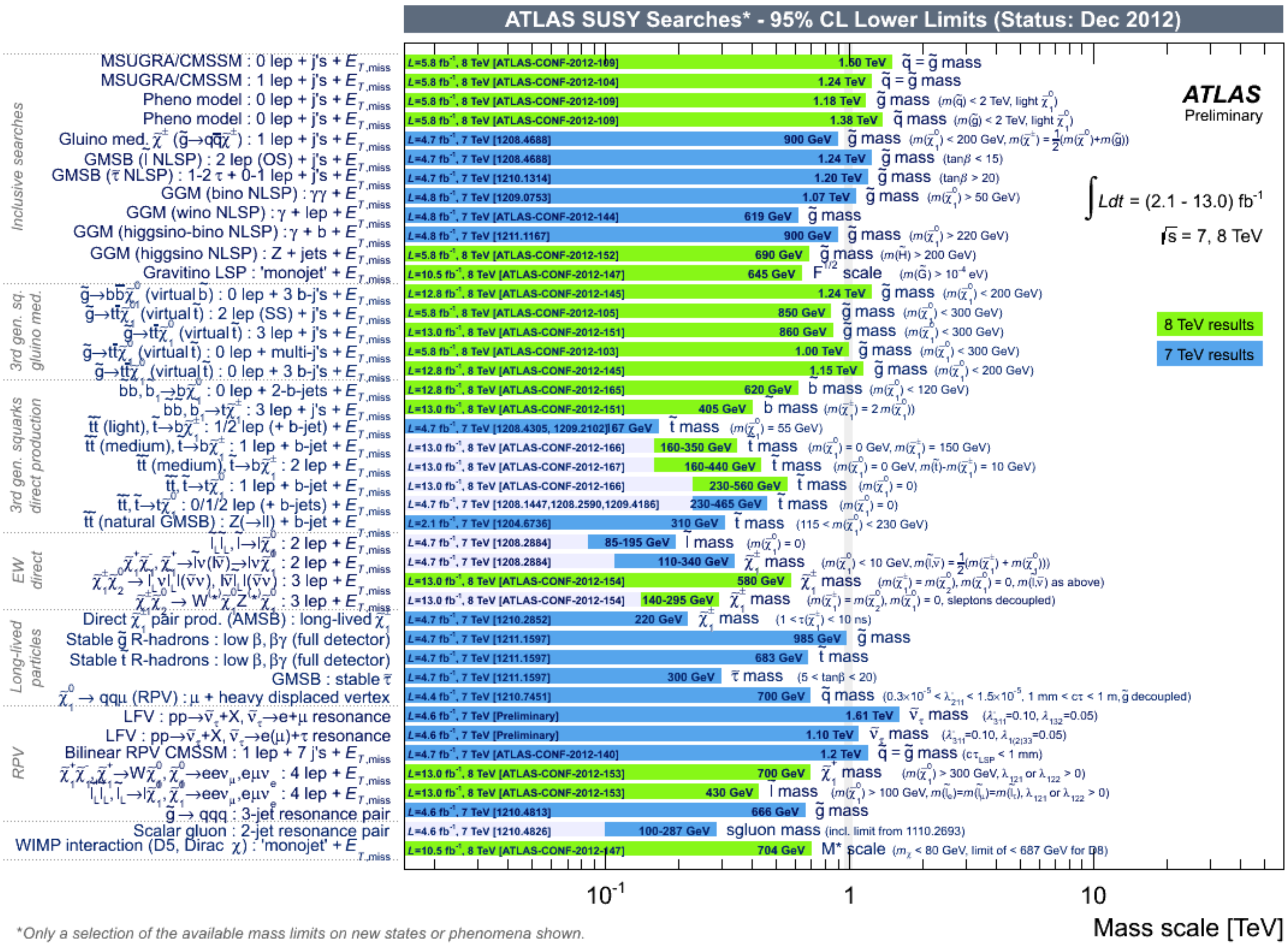
Arkani-Hamed, Dimopoulos '02

- give up on solving hierarchy problem
  - Still want Dark Matter candidate and gauge force unification
  - Squarks and sleptons heavy but gauginos and gluino light
- Could result in meta-stable gluinos
  - Experimental signature of long-lived charged massive particles
  - Identify through precise timing (β<1) and measurement of energy loss



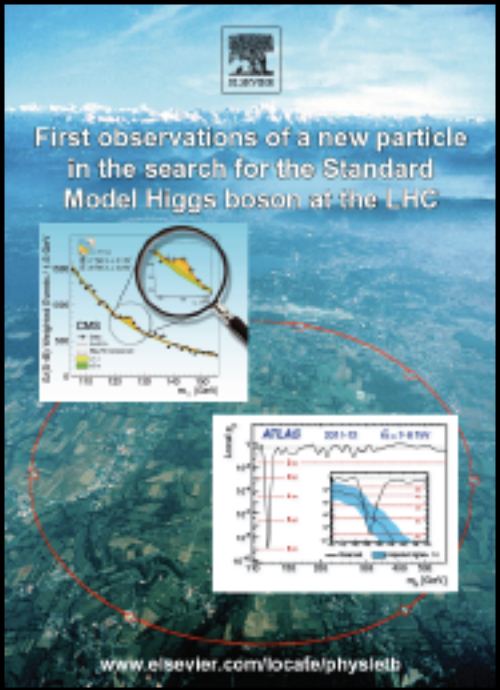
Gluinos excluded up to ~1 TeV

Summary of SUSY Searches



*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

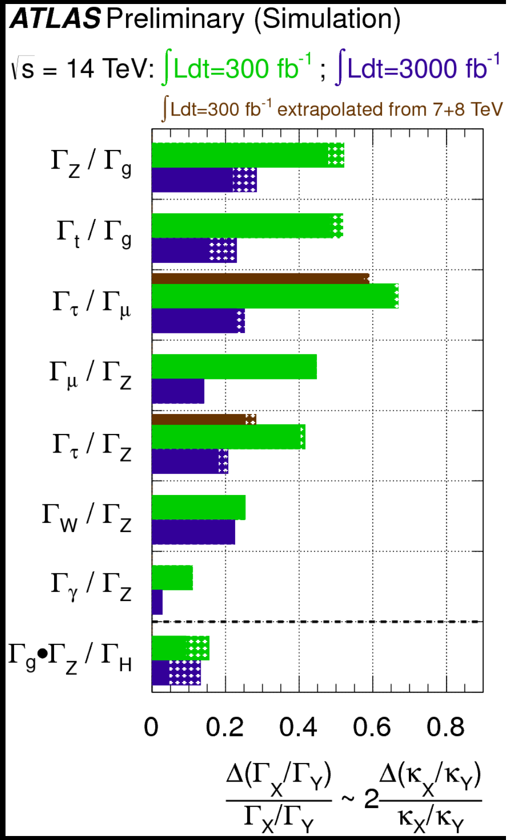
Conclusions & Outlook I



- The LHC works fantastically well
  - Already more than twice the Tevatron dataset at 4 times higher energy
- Found a new particle consistent with the Higgs boson
  - Program of property measurements is starting
    - Is it fully consistent with SM Higgs boson?
- No other new particles found (yet!)

Conclusions & Outlook II

- This was just the beginning!!!
  - High energy running starting in 2015 ($\sqrt{s} \approx 13$ TeV)
  - Increase luminosity by factor ~15 by 2021 and another factor 10 by 2030
    - Major detector upgrades required
  - Will probe
    - Higgs couplings with 2-10% precision
    - squarks and gluinos up to ~2.5 TeV
    - Stop quarks up to ~1 TeV



ATLAS upgrade week on Stanford campus

LHC time line

2009		✧ LHC startup, $\sqrt{s}$ = 900 GeV	
2010–2012		$\sqrt{s}$=7~8 TeV, L=6x10^{33} cm^{-2} s^{-1}, bunch spacing 50 ns	✔ Done ~20-25 fb^{-1}
2013–2014	LS1	Go to design energy, nominal luminosity (Phase-0)	
2015–2017		$\sqrt{s}$=13~14 TeV, L~1x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns	~75-100 fb^{-1}
2018	LS2	Injector and LHC Phase-I upgrade to full design luminosity	
2019–2021		$\sqrt{s}$=14 TeV, L~2x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns	Approved 300 fb^{-1} at 14 TeV
2022	LS3	HL-LHC Phase-II upgrade, IR, crab cavities	
2023 … 2030?		$\sqrt{s}$=14 TeV, L=5x10^{34} cm^{-2} s^{-1}, luminosity levelling	HL-LHC: 3000 fb^{-1} at 14 TeV

More Information

- Information, explanations, movies, images …
  - http://public.web.cern.ch
  - http://atlas.ch
    http://cmsinfo.cern.ch/outreach

Backup Slides

LHC milestones

- March 2007: last dipole magnet installed
- September 2008: first beam but major accident prevents LHC startup in 2008
- Nov. 2009: first collisions at injection energy (900 GeV)
- March 2010: first collisions at 7 TeV
  - 3.5 time higher energy than Tevatron
- End of 2010: $L=40\ pb^{-1}$ of data recorded
  - Sufficient to make many tests of Standard Model and to test supersymmetry beyond Tevatron
  - Not enough to test the Higgs
- End of 2011: $L=5\ fb^{-1}$ of data recorded
  - nearly 100 times more than 2010
  - Sufficient to probe Higgs boson over much of the mass range